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General Intelligence: Adaptation to Evolutionarily Familiar Abstract Relational Invariants, Not to Environmental or Evolutionary Novelty

Kenneth A. Koenigshofer

University of Maryland University College

Current formulations of the evolution of general (improvisational) intelligence leave unresolved a theoretical paradox first identified by Cosmides and Tooby (2002): given that natural selection requires recurrent, across-generation selection criteria, how can psychological mechanisms evolve that "exploit the novel features of unique situations"? Kanazawa (2004, 2010) and Chiappe and MacDonald (2005) sidestep this issue and consequently misconstrue general intelligence as an adaptation to novelty. Several new evolutionary principles resolve this problem, removing a significant roadblock for evolutionary theories of intelligence. Natural selection fashions mechanisms that accommodate fitness-related environmental regularities whenever they attain sufficient across-generation stability, even if attained only at abstract levels of recurrence. Variance in surface details of novel, nonrecurrent adaptive problems masks evolutionarily recurrent relational regularities forming a common problem structure captured by natural selection. Such "distilled" invariants, including similarity, covariation, and causality, provide across-generation selection criteria for evolution of seemingly domain-general processes, including categorization, generalization, inference, conditioning, causal–logical and analogical reasoning, as adaptive specializations. Innate, implicit knowledge of abstract, relational invariants constrains adaptively specialized learning, driving innovative solutions to otherwise unsolvable novel problems. Accordingly, general intelligence is not an adaptation to novelty, but emerges from adaptive specializations that genetically internalize abstract, relational regularities of the world.

Keywords: evolution of general intelligence, evolutionary novelty, *g* factor

> "If the contents of the human brain are domain specific, how can evolutionary psychology explain general intelligence?"
> Satoshi Kanazawa (2010)

> "What is sometimes required is not more data or more refined data but a different conception of the problem."
> Roger N. Shepard (1987b)

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General intelligence (GI) is one of the most pervasive concepts in psychology. It is typically defined as the ability to reason deductively and inductively, to think abstractly, to use analogies, to synthesize information, and to apply that information to new domains (Gottfredson, 1997; Neisser et al., 1996). General intelligence is at the root of our phylogenetically unprecedented technological achievements ranging from the invention of the wheel to quantum mechanics, and is arguably the basis for civilization itself. Yet, it harbors a troublesome paradox for evolutionary theory on at least two accounts (Barrett, Cosmides, and Tooby, 2007; Chiappe and MacDonald, 2005; Kanazawa, 2004; Kaufman, DeYoung, Reis, and Gray, 2011): [1] GI appears to be domain-general, when, by current evolutionary formulations, the mind should be comprised exclusively of domain-specific psychological adaptations to recurring conditions of the environment (Buss, 1995, 2008; Cosmides and Tooby, 1987, 1989, 1992, 2002; Gallistel, 1992, 1995, 2000; Kanazawa, 2004, 2010; Symons, 1990, 1992), and, [2] as Barrett et al. (2007) note, novel problems and situations, which presumably require GI, are "transient" and "[un]stable from a phylogenetic perspective," and therefore cannot provide across-generation basis for natural selection. In this paper, I resolve this evolutionary "enigma" (Cosmides and Tooby, 2002) by showing how GI evolved as a collection of adaptive specializations — not to some form of novelty as prior theorists have claimed (Chiappe and MacDonald, 2005; Kanazawa, 2004, 2010, 2012), but to phylogenetically recurrent, "evolutionarily familiar" (Kaufman et al., 2011) abstract relations found in nearly every adaptive problem and situation.

Psychometric g and General Improvisational Intelligence

The concept of general intelligence has formal origins in the work of early psychometricians. Spearman (1904, 1925, 1927, 1946), employing his factor analytic methods, discovered that scores on all mental tests were positively correlated (the "positive manifold") and that a common source of variance accounted for these positive correlations. These findings were interpreted by Spearman as evidence for a single, unitary general factor (*g*) in human intelligence. Spearman believed that *g* was most closely related to what he called the "eduction [from the Latin root *educere* which means to "draw out"] of relations and correlates," important in inductive and deductive logic, grasping relationships, inferring rules, and recognizing differences and similarities. Yet, the exact relationship between psychometric *g* and GI remains controversial. According to realist accounts, these abilities associated with *g* correspond to physical functions in the brain (Stedman, Kostelecky, Spalding, and Gagné, 2016, p. 200) which contribute to adaptation and which have been shaped by natural selection (Barrett, et al., 2007; Chiappe and MacDonald, 2005; Cosmides and Tooby, 2002; Kanazawa, 2004, 2010, 2012; Kaufman, et al., 2011). However, some have argued that the *g* factor and GI are not the same thing. Jensen (1998) maintained that individual differences in the *g* factor are probably most closely related to efficiency and speed of processing (see Borsboom and Dolan, 2006, for a similar view). Other psychologists favor a mutualism model which proposes that the *g* factor is merely a weighted sum of test scores, not a latent variable, not an explanation of the positive manifold (van der Maas, Kan, and Boorsboom, 2014), and therefore not identical to GI as a physical property of brains. By contrast, other psychologists suggest that from an empirical standpoint the *g* factor and GI are best considered identical and that multiple cognitive parameters contribute to *g*, with working memory capacity perhaps most closely related to *g* (DeYoung, personal communication, 2017). General intelligence, conceived as the ability for creativity and innovation, is perhaps best captured by Cosmides and Tooby's (2002) "improvisational intelligence." As a measure of reasoning ability, GI is often equated (e.g., see Kanazawa, 2010) with Cattell's (1971, 1987) "fluid intelligence" (Gf). Significantly, GI is found in many species and therefore is not an exclusive property of the human brain (Chiappe and MacDonald, 2005; Güntürkün and Bugnyar, 2016; Kabadayi and Osvath, 2017).

Evolutionary Origins of General Intelligence and the Pitfalls of Common Sense

When considering evolutionary origins of GI, most psychologists see GI as some form of adaptation to environmental or "evolutionary" novelty (e.g., Byrne, 1995; Chiappe and MacDonald, 2005; Kanazawa, 2004, 2010). This assumption is deeply embedded in current thinking among psychologists from a wide variety of specializations. For example, Cattell (1971, 1987) divided *g* into fluid (Gf) and crystallized (Gc) components and, according to Kvist and Gustafsson (2008, p. 423), *fluid intelligence* (i.e., general intelligence; Kanazawa, 2010) is the "ability to solve *novel*, complex problems using … inductive and deductive reasoning, concept formation, and classification" [italics added]. Along similar lines, in his triarchic theory of human intelligence, Sternberg (1988, 1990) emphasized the central role of human general intelligence in "coping with novelty." Likewise, Cosmides and Tooby (2002, pp. 146, 153) define "improvisational intelligence" as "the component(s) of an intelligent system designed to exploit transient or novel local conditions … to solve novel problems." In their evolutionary theory of GI, Chiappe and MacDonald (2005) propose that GI is a domain-general "adaptation to novelty and unpredictability" (p. 12) while Kanazawa (2004, 2008, 2010, 2012), in a series of influential papers, claims that GI is "nothing but" a *domain-specific* adaptation "to the sphere of evolutionary novelty" (2004, p. 514).

Most psychologists have come to accept one version or another of the general-intelligence-as-adaptation-to-novelty story. Although several evolutionary psychologists remain skeptical on theoretical grounds (Cosmides and Tooby, 2002; Kaufman et al., 2011; Penke, Borsboom, Johnson, Kievit, Ploeger, and Wicherts, 2011; Wicherts, Borsboom, and Dolan, 2010), for many psychologists it is “case closed” and all that remains is identification of the factors in evolutionary history that provided the novelty and unpredictability presumed to be responsible for the evolution of the human intellect (Ash and Gallup, 2007; Byrne and Whiten, 1997; Chiappe and MacDonald, 2005; Geary, 2009; Kanazawa, 2008, 2012).

Much of the appeal of the belief that GI is some form of adaptation to novelty undoubtedly derives from common sense. After all, we see evidence of human capability to deal with novelty all around us, and our ability to create novel solutions to adaptive problems is certainly a key component in the successes of the human species (e.g., Barrett et al., 2007; Byrne, 1995; Chiappe and MacDonald, 2005; Cosmides and Tooby, 2002; Geary, 2009; Kanazawa, 2004, 2008, 2010). However, common sense has been wrong before in the history of science. It was once self-evident that our planet was the center of the universe around which sun and moon and other heavenly bodies revolved. Common sense may blind us to logical contradictions in existing theories and cut off opportunity for a deeper understanding of nature (Kuhn, 1962).

Novel, Nonrecurrent Conditions Cannot be Captured by Natural Selection and therefore Cannot Explain Evolutionary Origins of General Improvisational Intelligence

As appealing as it seems on the surface, the widely accepted claim that GI had its evolutionary origins as some form of adaptation to novelty (Chiappe and MacDonald, 2005; Kanazawa, 2004, 2008, 2010, 2012) contradicts the fundamental tenets of modern evolutionary theory (e.g., Barrett et al., 2007; Cosmides and Tooby, 1992, 1995, 2002; Ermer, Cosmides, and Tooby, 2007; Kaufman et al., 2011; Penke et al., 2011) and therefore cannot be true. The only known mechanism for the evolution of complex adaptations is natural selection (Buss, 2008; Cosmides and Tooby, 1994, 2002; Symons, 1990, 1992) and natural selection requires *recurrent* across-generation conditions which can supply the enduring selection criteria needed to fashion adaptations over evolutionary time. As Tooby and Cosmides (1992, p. 69) state, “It is only those conditions that recur, statistically accumulating across many generations, that lead to the construction of complex adaptations” and as Cummins (1996, p. 166) notes, “Evolutionary theory is based on the assumption that there is a causal relationship between the adaptive problems a species *repeatedly encounters* during its evolution and the design of its phenotypic structures” [italics added]. In evolution, “Mutation proposes, natural selection disposes,” but only in the presence of *recurrent*, fitness-related (affecting survival and reproduction) conditions that act as enduring selection criteria over generations, thereby constraining the otherwise random walk of mutation and other chance processes in evolution.

This fact exposes the fundamental error (e.g., see Kaufman, 2012; Kaufman et al., 2011; Penke et al., 2011) in any theory (e.g., Chiappe and MacDonald, 2005; Kanazawa, 2004, 2010, 2012) which claims that GI originated as any form of adaptation to novelty. Novelty, by definition, means *non-recurrence* (Barrett et al., 2007; Cosmides and Tooby, 2002; Penke et al., 2011). Events, situations, and adaptive problems which are truly novel have not happened before and thus have not been "repeatedly encountered" during evolution; they are *not recurrent* across generations. Because truly novel problems and situations, by definition, are nonrecurrent, unique, local, and transient (Barrett et al., 2007; Chiappe and MacDonald, 2005; Cosmides and Tooby, 2002; Kanazawa, 2004, 2010), they cannot provide recurrent, across-generation criteria for natural selection, and without such enduring selection criteria, natural selection won't work (Barrett et al., 2007; Cosmides and Tooby, 2002; Kaufman et al., 2011; Penke et al., 2011).

As Tooby and Cosmides (1992, p. 69) state: "Long-term, across-generation recurrence of conditions … is central to the evolution of adaptations." But, novel, phylogenetically nonrecurrent problems, by definition, lack "across-generation recurrence of conditions," and therefore seemingly defy the laws of natural selection. "For selection to propel an allele consistently upwards, the relevant relationships between the environment, the organism, and the adaptive benefit must be stable: they must persist across many generations. For this reason, the functional designs of species-typical computational adaptations should, in general, both reflect and exploit conditions that hold true over long periods of time and over most or all of the species range" (Cosmides and Tooby, 2002, p. 175). Short-term, local, truly novel conditions and "novel, nonrecurrent problems" (Kanazawa, 2004, 2010, 2012) do not meet these requirements. They are not present "over long periods of time" nor does each such problem exist "over most or all of the species range." Given these facts, referring to what they call "the enigma of human intelligence," Cosmides and Tooby (2002, p. 177), ask: "By the nature of how natural selection works," how could general, "improvisational" intelligence, the component(s) of an intelligent system designed to exploit the distinctive features of transient or novel local conditions to achieve situation-specific improvisation, "be a nonmagical, genuine cognitive possibility"?

Chiappe and MacDonald (2005) and Kanazawa (2004, 2010) Recognize but Fail to Solve the Theoretical Problem Presented by Nonrecurrence of Conditions

Even the authors of the widely read papers claiming that GI is either "a domain-general adaptation to novelty and unpredictability" (Chiappe and MacDonald, 2005) or a "domain-specific adaptation to evolutionary novelty" (Kanazawa, 2004, 2010, 2012) recognize the theoretical difficulty presented by the absence of across-generation recurrence of conditions in novel situations and problems. Chiappe and MacDonald (2005, p. 10) write:

> Because recurrence is built into the definition of an adaptation, it implies there could be no adaptations designed to deal with novel, nonrecurrent problems: "Long-term, across-generation recurrence of conditions … is central to the evolution of adaptations" (Tooby and Cosmides, 1992, p. 69).

Nevertheless, the central claim in Chiappe and MacDonald's theory is that GI is "a domain-general adaptation to *novelty* [italics added] and unpredictability." To explain away this contradiction, Chiappe and MacDonald endeavor to redefine the concept of adaptation in an attempt to eliminate long-term, across-generation recurrence of conditions (what they call "statistically recurrent features of the environment") as a necessary condition for the evolution of adaptations by natural selection. However, by doing so, they contradict the Darwinian logic fundamental to the theory of evolution by natural selection since its inception — as noted above, "Long-term, across-generation recurrence of conditions … is central to the evolution of adaptations." Moreover, internal contradictions in their new definition of adaptation end up confirming the necessity for across-generation recurrence of conditions, the proposition they try to defeat. To wit, in their redefinition, the phrase "sufficient frequency" implies repetition — *recurrence*. The production of "functional outcomes" which "contribute to propagation with sufficient frequency over evolutionary time" (2005, p. 11) is possible *only if* the environmental conditions in which a trait "contribute[s] to propagation" are present over many generations (i.e., recurrent "with sufficient frequency over evolutionary time"). Thus, the concept of "statistically recurrent features" (p. 10) over generations as a requirement for evolution by natural selection, an idea which they reject, nevertheless stubbornly persists, hidden in their new definition of adaptation, in spite of Chiappe and MacDonald's explicit attempt to eliminate it. Consequently, their argument that general intelligence evolved, without recurrent conditions, as "a domain-general adaptation to novelty and unpredictability," collapses. Without recurrence, natural selection is impossible.

Similarly, Kanazawa (2004) repeatedly notes the difficulty for evolutionary theory presented by the nonrecurrence of conditions in "novel" problems. He writes:

> The evolution of psychological mechanisms assumes a stable environment; solutions cannot evolve in the form of psychological mechanisms if the problems keep changing…. By definition, we do not have prepared solutions in the form of evolved psychological mechanisms for novel, nonrecurrent problems. (p. 514)

Yet, contradicting his own logic, evolved psychological mechanisms for novel, nonrecurrent problems is exactly what Kanazawa proposes (2004, 2010, 2012) as the central claim of his theory that general intelligence evolved as a "domain-specific adaptation" to the "sphere of evolutionary novelty." If Kanazawa's evolutionary theory is right, then where are the recurrent conditions, across generations, required for evolution of GI? Novelty, the *nonrecurrence* of conditions, is the antithesis of what is required for evolution by natural selection. Kanazawa repeatedly acknowledges exactly this fact yet persistently ignores it. He states, "there are no dedicated modules to solve … evolutionarily novel problems" (Kanazawa, 2010, p. 282); nevertheless, the defining claim of his theory is that general intelligence *is* just such a mechanism, "a domain-specific adaptation" to "evolutionary novelty" in "novel, nonrecurrent problems."

Like Chiappe and MacDonald, Kanazawa attempts to get around the logical contradiction, but he also fails. He asserts that if "these evolutionarily novel, nonrecurrent problems happened frequently enough in the ancestral environment (a different problem each time) and had serious enough consequences for survival and reproduction, then … 'general intelligence' could have evolved as a domain-specific adaptation for the domain of evolutionarily novel, nonrecurrent problems" (Kanazawa, 2010, p. 281). But how can evolutionarily novel, nonrecurrent problems be *nonrecurrent* if they are happening "*frequently* enough"? "Frequently enough" certainly implies recurrence. How can "novel, nonrecurrent problems" be recurrent and nonrecurrent at the same time? This is the same logical problem which plagues Chiappe and MacDonald's (2005) concept of "sufficient frequency" (see above).

Even if we disregard this logical impossibility and grant that perhaps what Kanazawa *really* means by novel, nonrecurrent problems is *rare* (e.g., recurrent), adaptive problems for which there are no "prepared solutions" (contradicting his central claim that GI *is* a "prepared solution" for novel, nonrecurrent problems), this still will not salvage his "evolutionary novelty theory" of the evolution of GI. As Kaufman et al. (2011, p. 313) state in a critique of Kanazawa's (2010) theory: "Although rare events can have consequences for evolution if they affect sufficiently large numbers of a species, most rare events are likely to affect a small proportion of individuals, and their rarity will prevent them from exerting consistent selection pressure." This same idea is expressed by Cosmides and Tooby (2002, p. 175): "The incorporation of a trait into a species' design by [natural] selection is a large-scale, cumulative process, involving the summation of events that take place across the entire species' range and across a large number of generations." Kanazawa and his adherents want to stick with his common sense theory that GI originated as a domain-specific adaptation to "novel, nonrecurrent problems" even though "novel, nonrecurrent problems" now become, by Kanazawa's account, *recurrent* but rare problems, but not *too* rare — those rare ("nonrecurrent") problems that occur just "frequently enough." Kanazawa struggles to make novel, nonrecurrent problems into something else under the weight of the logical contradictions his theory requires. Yet, the notion that GI evolved as some form of adaptation to "novelty" is still widely accepted among many psychologists.

By contrast, consistent with my arguments, Penke et al. (2011) find Kanazawa's views of the evolution of GI logically and theoretically untenable. They state that Kawazawa's (2004, 2010) "'evolutionary novelty,' which is defined by exclusion (i.e., as everything not previously encountered in our evolutionary past), is not a coherent characterization of an adaptive problem. *Selection can only tailor domain specific* *adaptations to common problem structures*" (Penke et al., 2011, p. 916; italics added). Because *truly* "novel, nonrecurrent problems" lack "common problem structures," they cannot provide the across-generation selection criteria needed to drive the evolution of complex adaptations (Barrett et al., 2007; Cosmides and Tooby, 2002; Cummins, 1996; Ermer et al., 2007) such as GI. As Kanazawa (2004, p. 514) states, contradicting the central claim of his own "evolutionary novelty" theory, "we do not have … evolved psychological mechanisms for novel, nonrecurrent problems." Clearly, there is something missing from the evolutionary analyses of Kanazawa (2004, 2008, 2010, 2012), Chiappe and MacDonald (2005), and others who claim that GI has its evolutionary origins as any form of adaptation to novelty.

Kanazawa's Concept of "Evolutionary Novelty" Misses the "Common Problem Structures"

The major difficulty with the theories of Chiappe and MacDonald and Kanazawa, which attempt to explain the evolutionary origins of GI as some form of adaptation to environmental or evolutionary novelty, is their failure to look for and to identify the phylogenetically recurrent, "common problem structures" that characterize so-called "novel, nonrecurrent" problems. As noted above, "Selection can only tailor domain specific adaptations to common problem structures" which can provide phylogenetically recurrent criteria for selection over generations.

However, a more careful evolutionary analysis reveals that recurrence of "common problem structures" (Penke et al., 2011) *does* exist in so-called novel problems, but the recurrent structure is not in their novelty or nonrecurrence. Rather, it is in enduring, evolutionarily *familiar* (Kaufman, et al., 2011) relational regularities present in nearly all adaptive problems, including so-called "novel, nonrecurrent" ones.

Evolutionarily Familiar Relational Invariants Drove the Evolutionary Origins of General "Improvisational" Intelligence

From my perspective, these evolutionarily *familiar* relational regularities or invariants reflect enduring, fundamental properties of the world, and include *similarity* (James, 1890/1950; Penn, Holyoak, and Povinelli, 2008; Shepard, 1987a, 1987b; Wasserman, Hugart, and Kirkpatrick–Steger, 1995), predictive event *covariation* (Gelman and Legare, 2011; Gopnik, Sobel, Schulz, and Glymour, 2001; Kaufman, et al., 2011; Kushnir and Gopnik, 2007; Wasserman, 1993a), and *causality* (Clark, 2013; Fales and Wasserman, 1992; Gelman and Legare, 2011; Gopnik, 2010, 2012; Gopnik and Wellman, 2012; Kaufman, et al., 2011; Penn et al., 2008; Pinker, 1997, 2007; Walker and Gopnik, 2014; Wasserman, Elek, Chatlosh, and Baker, 1993; Wasserman, Kao, Van Hamme, Katagiri, and Young, 1996). As I will show, these abstract relational invariants, recurrent over generations across situations and adaptive problems, provided the enduring, across-generation selection criteria (missed by prior theorists) which drove the evolution of the primary problem-solving engines of GI.

According to Shepard (1987a, 1992, 1994, 2001), natural selection has favored the genetic incorporation or “internalization” of representations which exploit biologically relevant regularities of the world, “whether … within a particular species' local niche or throughout all habitable environments.… Genes that have internalized these pervasive and enduring facts about the world should ultimately prevail over genes that leave it to each individual to acquire such facts by trial and possibly fatal error” (1994, p. 2). Shepard argues that “the evolutionary internalization of universal regularities” (1994, p. 26)[1] has included invariant properties such as “three-dimensional, locally Euclidian space” with a "gravitationally conferred unique upward direction," one-dimensional time with a "thermodynamically conferred unique forward direction," cycles of light and dark, and the recurrent fact of the world that "objects having an important consequence are of a particular natural kind … however much those objects may vary in their sensible properties … " (1992, p. 500). Shepard’s last example of genetic/evolutionary internalization is the basis for his “universal law of generalization” (1987b), verified in diverse species including insects (e.g., see Cheng, 2000).

From my perspective, such “general — perhaps even universal — properties” (Shepard, 1992, p. 500) which have been genetically/evolutionarily internalized also include abstract relational regularities or invariants of the world: cause–effect, predictive event covariation, and similarity relations.[2] Just as natural selection has exploited regularities in the problem structures associated with cheater detection, mate selection, and predator avoidance to fashion “dedicated” mechanisms for these (Buss, 2008; Cosmides and Tooby, 2002), natural selection has also exploited heretofore unrecognized (Chiappe and MacDonald, 2005; Kanazawa, 2004, 2010, 2012) abstract relational invariants of the world, evolving the problem-solving mechanisms of GI. The genetic internalization by natural selection of these relational regularities has equipped the mind with innate, abstract, rule-like principles of how the world works. Deployment of this abstract, implicit “knowledge” or “understanding” about causality, predictive event covariation, and similarity relations gives GI its adaptive punch and permits innovative and improvisational solutions to adaptive problems of near limitless variety — problems, which, though variable or even “novel” in details, are nevertheless invariant in common relational structure. That recurrent, common problem structure drove the evolution of GI. From this perspective, general fluid “improvisational” (Cosmides and Tooby,

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[1] Shepard uses the terms “genetic internalization” (1992, p. 498) and “evolutionary internalization” (1994, p. 26) interchangeably. In this paper, I shall do the same.

[2] It is my claim that other properties, such as logic, for example, are derived from these, as natural selection fine-tuned the mechanisms of human GI over evolutionary time, perhaps, at least partially, in conjunction with the evolution of language mechanisms.

2002) intelligence did not originate as any kind of adaptation to novelty as claimed by prior theorists (Chiappe and MacDonald, 2005; Kanazawa, 2004, 2010, 2012), but instead evolved as a collection of adaptive specializations to these evolutionarily *familiar*, abstract relational regularities common to nearly all situations and adaptive problems.

The Mechanisms of General Intelligence as Adaptive Specializations

From my perspective, these psychological adaptations of GI are *adaptive specializations* because each evolved by natural selection in response to a particular, identifiable, across-generation regularity of the world which, as I will show, provided enduring, across-generation basis for selection (see Kaufman, 2012; Kaufman et al., 2011). In this way, these problem-solving mechanisms of GI are just another category of "dedicated intelligences" (Cosmides and Tooby, 2002). However, the domains of these mechanisms of GI are abstract, relational properties or invariants (e.g., causality, covariation, and similarity) found ubiquitously in the world, accounting for the impression that these adaptive specializations are "domain-general," or "content-free" (Cosmides and Tooby, 1992, 2002), while, in fact, their content is actually quite specific, although abstract and relational (and universal, and therefore in this sense only, domain-general). Therefore, I refer to these mechanisms of GI as *content-abstracted adaptive specializations of the mind* (CAASMs). Each has "genetically internalized" (Shepard, 1992) a particular abstract, across-generation, relational invariant of the world (causality, covariation, or similarity). Table 1 compares this formulation of the evolution of general intelligence with the theories of Chiappe and MacDonald (2005), Cosmides and Tooby (2002), Kanazawa (2004, 2010), and general process (GP) views typical of the Standard Social Science Model (Cosmides and Tooby, 1992).

This formulation is reminiscent of Cosmides and Tooby's (2002) "bundling hypothesis" (Table 1) which proposes that general improvisational intelligence emerges from interactions among large numbers of the traditionally defined domain-specific dedicated intelligences (e.g., mate selection module, cheater detection module, etc.), except, from my perspective, the "bundle" is a collection of heretofore unidentified adaptive specializations to evolutionarily familiar, across-generation, abstract relational invariants (I_i). What appear to be diverse psychological processes such as causal and analogical reasoning, conditioning, categorization, generalization, logic, concept formation and inference, are, in fact, families of processes (or properties) originating from the genetic/evolutionary internalization (Shepard, 1992, 1994) of causality, covariation, and similarity relations, respectively, by evolutionary processes I outline later in this paper. Members of each family share properties in common because cognitive processes of the same family originate from internalization of the same invariant.

Table 1
Overview of Several Evolutionary Theories of General Intelligence (GI)

Theory	Proposed Mechanism(s)	Criteria for Natural Selection	Nature of Learning
Chiappe and MacDonald (2005)	"domain-general adaptation to novelty and unpredictability"	no selection criteria; C and M argue for evolution without "statistically recurrent features"	domain-general, "content-independent"; some innate content in conditioning
Cosmides and Tooby (2002)	"bundle" of adaptively specialized, domain-specific, "dedicated intelligences" (e.g., mechanisms for cheater detection, mate selection, etc.)	selection criteria for evolution of GI are the same as those for evolution of the domain-specific "dedicated" mechanisms	domain-specific and adaptively specialized
Kanazawa (2010)	"a domain-specific adaptation to evolutionary novelty" but comprised of mechanisms usually described as "domain-general" such as "thinking and reasoning"	rare instances of "novel, nonrecurrent problems" in an otherwise constant Pleistocene EEA (environment of evolutionary adaptedness)	not specified, but implies domain-general
Evolutionarily familiar relational invariants hypothesis (proposed in this paper)	"content-abstracted" adaptive specializations (CAASMs) which genetically internalize evolutionarily recurrent, abstract relational invariants (e.g., causality, covariation, similarity)	abstract relational invariants in the across-generation "deep" structure of adaptive problems (variable in "surface structure" details)	adaptively specialized; rich in innate content; exploits across-generation invariants in problem structures
General process (GP) theories of GI	logic, reasoning, inference, thinking, learning, conditioning	none specified; evolutionary origins typically not addressed	general; not adaptively specialized; little if any innate content

Kanazawa's "Evolutionarily Novel Problems" are Actually Evolutionarily Familiar

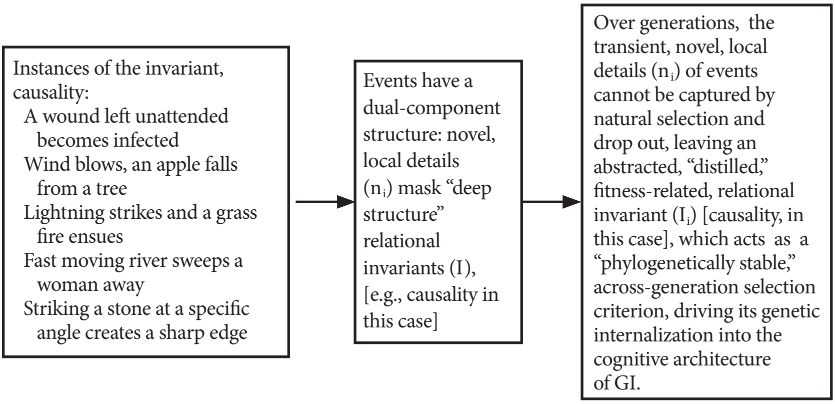
To illustrate these ideas, a good starting point is a closer examination of Kanazawa's concept of "evolutionary novelty," the key concept in his evolutionary theory of GI. Careful analysis of Kanazawa's (2004, 2010) examples of so-called evolutionary novelty reveals that the concept is fatally flawed because it misses the recurrent, *evolutionarily familiar* structure present in all adaptive problems — including those which Kanazawa claims are "evolutionarily novel." In fact, no situation, condition, or adaptive problem is ever entirely novel. Every situation or adaptive problem has recurrent, evolutionarily *familiar* elements (e.g., causality, event covariation, and similarity relations) in addition to any novel elements which might also be present. That is, any event, situation, or adaptive problem, E, has novel elements in the details (n_i), but also has more abstract relational elements which are evolutionarily familiar and recurrent, or even invariant (I_i), over generations.

"Distilled" Relational Invariants as Selection Criteria

These evolutionarily recurrent abstract relational invariants (I_i), each "distilled" out of innumerable detail-variable instances of the relational invariant over generations, can act as stable selection criteria driving evolution of psychological adaptations which "genetically internalize" (Shepard, 1992) these invariants into the cognitive architecture. Figure 1 illustrates these ideas for *causality*. Similar dynamics apply to the genetic internalization of *predictive event covariation* and *similarity* relations as broad, abstract principles of how the physical world is organized.

A general principle is at work here: events, situations, and adaptive problems that are variable in transient, local (i.e., phylogenetically nonrecurrent) "novel" details (n_i) mask abstract, across-generation (i.e., phylogenetically recurrent; evolutionarily familiar) relational invariants (I_i). Because natural selection operates over generations, transient, local, novel details (n_i) cannot be captured by natural selection and are therefore "washed out" over generations leaving "distilled," phylogenetically recurrent (evolutionarily familiar), relational invariants (I_i) which can act as stable, across-generation selection criteria driving their genetic/evolutionary internalization into the cognitive architecture. These evolutionary dynamics may be called the *principle of distilled invariants* (DInv). On my view, these dynamics of natural selection explain the evolutionary origins of the problem-solving engines of general fluid "improvisational" intelligence.

Symbolically, every event, situation or adaptive problem can be represented as $E_{i\ (\text{event or adaptive problem})} = I_i + n_i$. This dual-component structure of events and adaptive problems reflects the general structure of the physical world derived from its natural laws. By this analysis, Kanazawa's examples of evolutionarily novel, nonrecurrent adaptive problems are only "novel and nonrecurrent" in their case-specific surface details (n_i), but evolutionarily *familiar* (phylogenetically recurrent) in underlying deep relational structure (I_i). Because natural selection operates over many generations (Cosmides and Tooby, 2002), it is only these recurrent, evolutionarily familiar "deep structure" elements in Kanazawa's so-called "evolutionarily novel problems" that can be captured by natural



Instances of the invariant, causality:

- A wound left unattended becomes infected
- Wind blows, an apple falls from a tree
- Lightning strikes and a grass fire ensues
- Fast moving river sweeps a woman away
- Striking a stone at a specific angle creates a sharp edge

Events have a dual-component structure: novel, local details (n_i) mask "deep structure" relational invariants (I), [e.g., causality in this case]

Over generations, the transient, novel, local details (n_i) of events cannot be captured by natural selection and drop out, leaving an abstracted, "distilled," fitness-related, relational invariant (I_i) [causality, in this case], which acts as a "phylogenetically stable," across-generation selection criterion, driving its genetic internalization into the cognitive architecture of GI.

Figure 1: The principle of distilled invariants (DInv) applied to causality. Shown for illustration are several examples of the countless instances, over evolutionary time, of one abstract relational invariant (I_i), causality. The events shown at the left are variable in idiosyncratic, local, novel details (n_i) but all share the same relational invariant (I_i). Over generations, novel, local details, too transient to be captured by natural selection, drop out, leaving a "distilled" relational invariant (e.g., causality) which persists over the species range and over generations. This relational invariant provides a "phylogenetically stable" (across-generation) basis for selection, causing genetic internalization of the invariant (causality, in this case), forming a primary problem-solving mechanism of GI. Similar evolutionary dynamics apply to predictive event covariation and similarity relations, forming additional mechanisms of GI. Note that because natural selection operates over many generations, the transient, evolutionarily nonrecurrent, novel details (n_i) of adaptive problems cannot provide enduring selection criteria, and therefore cannot drive evolution of adaptations such as GI, contradicting the claims of prior theorists such as Kanazawa (2004, 2010, 2012) and Chiappe and MacDonald (2005).

selection and which could act as selection criteria for the evolutionary origins of GI; the "novel" elements (n_i) are too "transient and local" (Cosmides and Tooby, 2002) to be captured by natural selection and therefore "drop out" (are lost) over generations. Because the novel details (n_i) are too transient, variable, and nonrecurrent to be captured by natural selection, they cannot be directly incorporated into genetic mechanisms and therefore cannot be the basis for the evolutionary origins of GI. This conclusion is predictable from the arguments above that natural selection can only fashion complex adaptations in response to conditions of the environment that are recurrent over many generations, and which are therefore evolutionarily familiar.

Kanazawa's Examples of "Evolutionary Novelty" are Packed with Evolutionarily Familiar Elements

Kanazawa (2004, 2010) offers three examples of what he calls "novel, nonrecurrent problems," central to his "evolutionary novelty theory" of the evolution of GI:

> 1. Lightning has struck a tree near the camp and set it on fire. The fire is now spreading to the dry underbrush. What should I do? How can I stop the spread of the fire? How can I and my family escape it? (Since lightning never strikes the same place twice, this is guaranteed to be a nonrecurrent problem.)
>
> 2. We are in the middle of the severest drought in a hundred years. Nuts and berries at our normal places of gathering, which are usually plentiful, are not growing at all, and animals are scarce as well. We are running out of food because none of our normal sources of food are working. What else can we eat? What else is safe to eat? How else can we procure food?
>
> 3. A flash flood has caused the river to swell to several times its normal width, and I am trapped on one side of it while my entire band is on the other side. It is imperative that I rejoin them soon. How can I cross the rapid river? Should I walk across it? Or should I construct some sort of buoyant vehicle to use to get across it? If so, what kind of material should I use? Wood? Stones? (Kanazawa, 2004, p. 514; 2010, p. 281)

By these examples, Kanazawa intends to illustrate what he means by evolutionary novelty, so-called novel, nonrecurrent adaptive problems for which, he argues, “we do not have … evolved psychological mechanisms” (2004, p. 514) because such problems were “unanticipated by evolution” (Kanazawa, 2010, p. 282). However, these and other so-called novel situations and novel adaptive problems are actually packed with evolutionarily familiar relational invariants (I_i), in their problem structure, and thus, contrary to Kanazawa’s understanding, they *were*, in fact, “anticipated by evolution” (similarly, climatic fluctuation in Pleistocene environments did not result in events that were as “novel and unpredictable” as Chiappe and MacDonald, 2005, argue. Instead, the novelty and unpredictability was only in evolutionarily transient, idiosyncratic details (n_i), not in the predictable relational invariants (I_i) such as cause–effect, event covariation, and similarity relations. These relational invariants and the physical laws of nature which underlie them were not suddenly suspended during the Pleistocene, but instead were exploited, as in prior environments, to solve adaptive problems).

Kanazawa (2004, 2010) fails to see the common problem structures in his examples of evolutionarily novelty. In each of his examples, there certainly are novel, transient, local details (n_i), but also present are more adaptively important evolutionarily *familiar* elements — recurrent, across-generation relational invariants (I_i) common across adaptive problems and situations. It was these relational invariants (I_i) that were captured by natural selection to form the problem-solving mechanisms of GI, not the short-term, nonrecurrent novel elements (n_i), as Kanazawa and others have claimed.

Kanazawa’s reluctance to recognize common problem structures in instances which vary only in terms of their idiosyncratic details (n_i) is most clearly illustrated by his quip, “Since lightning never strikes the same place twice, this is guaranteed to be a nonrecurrent problem” (Kanazawa, 2004, p. 514; 2010, p. 281).

But does variation in location of a natural event such as lightning, which is obviously a repeated and widely distributed phenomenon in the natural world, mean that lightning or lightning-caused fires are therefore "evolutionarily novel"? Kanazawa's analysis here is like saying that whenever gravity acts on an object in a different location on the Earth (like lightning at different locations) that each such instance of gravity constitutes an "evolutionarily novel, nonrecurrent" event. By this reasoning, if an apple falls on Newton's head in Yorkshire and then again in London, then using Kanazawa's logic these are distinct "evolutionarily novel" events because they occurred in different locations; moreover, if Kanazawa were correct, there would be no common structure between these instances of the action of gravity in different locations and thus no general law of gravitation for Newton to discover. Clearly, Kanazawa cannot be correct. (Furthermore, even "dedicated" mechanisms must respond to "novel," phylogenetically "transient" details. For example, the mate selection module which utilizes, in part, the female hip-to-waist ratio [Singh, 1993] encounters women who vary from one another in many idiosyncratic "novel" details and who appear in many different locations, like Kanazawa's lightning strikes — nevertheless each woman is not evolutionarily novel as Kanazawa's logic implies). In fact, each of Kanazawa's examples of a "novel nonrecurrent problem" actually contains the highly adaptively significant, evolutionarily *familiar* elements (I_i) described above — abstract, across-generation, relational invariants (I_i) including causality, covariation, and similarity relations.

Consider Kanazawa's first example of evolutionary novelty. It includes an adaptively significant cause–effect relation between lightning and fire; there are important predictive covariations between lightning and fire that a problem-solver might use to discover the specific cause–effect relation (just as small children discover cause–effect relations by use of statistical covariations between events; e.g., see Gopnik, 2010, 2012; Gopnik and Sobel, 2000; Walker and Gopnik, 2014); and there are potentially highly adaptively useful similarity relations between this lightning strike and others previously encountered (adaptively important similarities are present even if the lightning did not strike "in the same place twice," contrary to Kanazawa's puzzling claim that each lightning strike is an evolutionarily novel, nonrecurrent event, without adaptively significant similarities to others).

Clearly, in this first example of evolutionary novelty offered by Kanazawa, a hypothetical Pleistocene problem-solver's understanding of the problem presented by the lightning-caused fire would depend critically upon exploitation of similarity between lightning strikes, and similarities in the cause–effect relation between fire and its destructive effects on things in its path, which predicts, in the current situation, destruction of one's camp and family. Furthermore, formulation of a solution to the problem presented by the brush fire would be critically dependent upon the problem-solver exploiting the cause–effect relation between fire and substances such as water or dirt which might extinguish the fire. This would require knowledge gained by observation of the effect of these causal measures on fires, either in current trial and error (that is, throw water or dirt on fire and see if the fire goes out) and/or by the similarity of the current situation to past encounters with fire and similar fire-retardant substances. Novel details (n_i) in Kanazawa's first example of "evolutionary novelty" are much less important to problem-solution than the evolutionarily familiar abstract, relational invariants (I_i) in the problem.

These invariants (I_i) hidden in Kanazawa's example of so-called "evolutionary novelty," although subtle, relational, and abstract (and completely missed by Kanazawa and by Chiappe and MacDonald; perhaps because their very ubiquity may blind us to them; Shepard, 1987a, 1987b, 1994), are nevertheless real, evolutionarily familiar, and recurrent across generations and could therefore drive natural selection, while novel details (n_i) in so-called evolutionary novel nonrecurrent problems cannot, because they are phylogenetically nonrecurrent and therefore cannot provide stable across-generation selection criteria. As noted above, all events, situations, and problems have the dual-component structure represented by $E_{i\,(\text{event, adaptive problem})} = I_i + n_i$. However, over generations, over repeated instances of the particular class of problem ($E_i = I_i + n_i$), the "novel, nonrecurrent" transient details (n_i) "drop out" and are lost to natural selection, leaving only the relational invariant, I_i, to be captured and internalized by natural selection into the mechanisms of GI (functionally, for natural selection, $E = I_i$, not $E = n_i$ as prior theories imply). In essence, natural selection is "blind" to the nonrecurrent, transient, novel details (n_i). Therefore, novelty (n_i) cannot be the evolutionary origin of the mechanisms of GI as Kanazawa and others (e.g., Chiappe and MacDonald, 2005) claim; instead GI originated as adaptive specialization to the recurrent, across-generation, evolutionarily familiar, invariants (I_i) in the structure of nearly all adaptive problems, situations, and events: cause–effect, covariation, and similarity relations.

Supporting this view, research showing that humans skillfully exploit and demonstrate sophisticated understanding of causality, event covariations, and similarity relations from an early age, even when these relations are highly abstract (Penn et al., 2008; Walker and Gopnik, 2014), suggests that representations of these relational invariants, as general, abstract principles of how the world works, must have been incorporated by evolution into the human mind as standard equipment long ago (e.g., see Gopnik, 2010, 2012; Gopnik et al., 2001; Gopnik and Sobel, 2000; and Walker and Gopnik, 2014, for evidence that understanding and skillful exploitation of causality and covariation are present in very young children, and are probably innate; Penn et al., 2008, discuss comparable findings in young children for highly abstract similarity and causal relations).

In Kanazawa's second and third examples of "evolutionary novelty," once again we find highly adaptively important evolutionarily familiar, across-generation, relational invariants (I_i), missed entirely by Kanazawa. Note that these evolutionarily familiar relational regularities or invariants (I_i), *not the novel details* (n_i), provide the problem-solver with a “common problem structure” without which the problem would be unsolvable.

This analysis applies not only to Kanazawa’s examples of evolutionary novelty but to all novel situations and adaptive problems. As noted above, all events, situations, and problems are simultaneously novel (in their idiosyncratic details) and yet recurrent (even invariant) across generations in their underlying abstract, relational structure ($E_i = I_i + n_i$). In other words, quite significantly, some of the components of novel situations and novel adaptive problems (namely I_i, the across-generation, relational invariants including causality, event covariation, and similarity) are actually quite “stable from a phylogenetic perspective” (Barrett et al., 2007, p. 244). Therefore these invariants could provide the enduring selection criteria, the “long-term, across-generation recurrence of conditions … central to the evolution of adaptations" (Tooby and Cosmides, 1992, p. 69), thereby explaining the evolutionary origins of the problem-solving mechanisms of GI (other components of GI such as explicit attentional and working memory systems are not the primary focus of this paper; for discussion of these and GI, see Geary, 2005).

General Improvisational Intelligence and Evolved Learning Mechanisms

This analysis suggests a path for greater integration of evolutionary thinking into the study of learning (Papini, 2002). It makes clear why learning mechanisms evolve, why they take the forms that they do, and why learning mechanisms are integral to the mechanisms of GI. Consider the dual-component structure of events in the world ($E_i = I_i + n_i$). Because natural selection operates over generations, it can only capture and genetically internalize the former (I_i), while the phylogenetically short-term, variable details (n_i) are lost to natural selection. These (n_i) are captured by learning mechanisms specifically evolved for this function. From these fundamental facts two broad generalizations can be derived.

First, natural selection tailors mechanisms which genetically internalize (Shepard, 1994) fitness-related (i.e., adaptively significant) environmental regularities *whenever* these regularities attain across-generation stability sufficient to provide enduring, across-generation selection criteria, even when the requisite stability is attained only at abstract levels of event recurrence. Consequently, selection operates on fitness-related environmental regularities at multiple levels of abstraction fashioning adaptations which genetically incorporate or internalize abstract regularities or invariants (I_i) into their evolved functional organization. The adaptive specializations of GI proposed in this article are examples; “core knowledge” (Spelke, 2003), “intuitive physics” (Baron–Cohen, Wheelwright, Spong, Scahill, and Lawson, 2001), “intutive theories” (Gopnik and Wellman, 2012), and “innate ideas” (Cosmides and Tooby, 2013; Delton and Sell, 2014; Pinker, 1997; Tooby, Cosmides, and Barrett, 2005) are others.

Second, whenever information in evolutionarily recurrent, across-generation fitness-related regularities alone is insufficient, over evolutionary time, to the specification of a solution to a phylogenetically recurrent adaptive problem because information contained in more variable, local, transient events must be added to achieve problem solution, then an adaptively specialized learning mechanism will evolve, and the innate structure of the learning mechanism will be dictated by the elements of the problem structure with sufficient across-generation stability to be captured by natural selection. This *principle of evolved learning mechanisms* (ELM) implies that all learning is specialized (a view advocated by Gallistel, 1992, 2000). Additionally, it predicts that each type of learning has innate, evolved structure in the form of implicit "knowledge" about those more general, abstract, and evolutionarily recurrent features (I_i) of the learning situation which are sufficiently stable over generations to be captured and genetically internalized by natural selection. This genetically internalized, implicit "knowledge" about invariants in the learning situation pre-structures the learning, facilitating the capture of the problem-relevant details too variable, local, and short-term to be captured directly by natural selection in genetic mechanisms. This is seen in human causal learning (i.e., Gopnik, 2010, 2012; Walker and Gopnik, 2014) and in other learning mechanisms of GI. However, the principle is even more general.

Well-known examples illustrating this principle are the concepts of biological constraints or biological preparedness first described in taste aversion and fear learning (Garcia and Koelling, 1966; Seligman, 1971), but these are special cases. This principle has even wider applicability. It predicts and explains the structure and functional dynamics of a broad range of learning mechanisms including human language acquisition (e.g., an innate deep structure in the form of a "universal grammar" plus biologically prepared learning of the details of one's own language); learning of the solar ephemeris by honeybees (genetic/evolutionary internalization of the regularity that the sun is always somewhere in the east in the morning and in the west in late afternoon facilitating learning of local features of the ephemeris for navigation; Dyer and Dickinson, 1994); causal learning by children (innate, genetically internalized knowledge of cause–effect and patterns of covariation guide learning about specific cause–effect relations in one's specific experience; Gopnik, 2010, 2012; Walker and Gopnik, 2014); learning of the location of the current north star in Indigo buntings (rotation of the night sky about an apparently stationary pole star provides a genetically internalized invariant cue for the learning of a specific navigational beacon, the current north star, which varies too rapidly to be genetically internalized because of the Earth's axial precession; Gallistel, 1992); song acquisition in white crowned sparrows (an innate, genetically internalized song template guides learning of local dialects of the species song); imprinting in precocial birds (imprinting object must be larger and moving); and even so-called "general" forms such as conditioning, which from my perspective are also adaptively specialized (see Gallistel, 1992, 1995, 2000 for a similar view) and genetically pre-loaded with constraints — for example, several genetically internalized "default assumptions" built into conditioning and causal learning mechanisms by natural selection are that "causes are reliable predictors of their effects, that causes precede their effects,... that in general, causes tend to occur in close temporal proximity to their effects ... and the temporal contiguity of cause and effect is a general feature of the world" (Chiappe and MacDonald, 2005).[3]

In each learning mechanism, information about specific, enduring across-generation regularities or invariants, which has been captured and genetically internalized (Shepard, 1992, 1994) by natural selection, is supplemented by learning mechanisms specialized to capture problem-relevant informational details too transient, local, and variable (evolutionarily/phylogenetically nonrecurrent) to be captured by natural selection directly via genetic internalization. Each learning mechanism (by virtue of the principle of distilled invariants, DInv; Figure 1) has innate structure dictated by enduring, across-generation invariants of the world, even in the case of learning mechanisms which appear to be "general" (rather than adaptively specialized) because of the wide distribution of the invariants which have been genetically internalized into them.

General Intelligence Originated as Adaptive Specialization to Evolutionarily Familiar Abstract Relational Regularities of the World, Not to Novelty

Based on the arguments above, clearly GI cannot have its evolutionary origins as any kind of adaptation to evolutionary (Kanazawa, 2004, 2010, 2012) or environmental novelty (Chiappe and MacDonald, 2005), as widely believed. Not only are truly novel situations and adaptive problems nonrecurrent over generations and therefore incapable of providing across-generation selection criteria that can be captured by natural selection, but, additionally, so-called "evolutionarily novel problems" are actually replete with highly adaptively significant evolutionarily familiar elements (I_i). The short-term, local, *novel details*, in the "surface structure" of problems like those Kanazawa uses to illustrate what he means by "novel, nonrecurrent problems" or "evolutionarily novel problems," are *not* recurrent across generations, *cannot* be captured by natural selection, and therefore *cannot* serve as selection criteria for the evolution of any complex adaptation, including GI. Instead, evolutionarily familiar relational invariants *are* recurrent across generations and *are* captured by natural selection (the principle of distilled invariants; Figure 1) resulting in a "bundle" of adaptive specializations which have genetically internalized

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[3] In addition, from this perspective, the fact that conditioning — except in taste aversion learning — generally requires multiple pairings of CS and UCS, or of operant response and its effect, is *not* a shortcoming or a "weakness" of conditioning processes but rather may be an evolved adaptive feature of conditioning fashioned by natural selection to prevent formation of potentially spurious and therefore, maladaptive associations.

(Shepard, 1994) these *evolutionarily familiar* (phylogenetically recurrent), abstract, across-generation, relational invariants (causality, predictive event covariation, and similarity relations) forming the problem-solving mechanisms of GI.

To support his evolutionary novelty theory, Kanazawa claims that individual differences in psychometric *g* should be correlated with ability to solve evolutionarily novel problems, but *not* evolutionarily familiar ones. However, contradicting Kanazawa's prediction, Kaufman et al. (2011) report that *g* predicts reasoning ability even for evolutionarily familiar content, consistent with my formulation. Furthermore, the logic behind the correlational evidence Kanazawa (2010) uses to support his theory has been called into question (Penke et al., 2011), and because Kanazawa's data are correlational his data are subject to multiple alternative explanations that may not support his claim that general intelligence originated as an adaptation to evolutionary novelty (Kaufman et al., 2011).

This is not to say that general improvisational intelligence does not facilitate solutions to new problems. Surely it does. However, simply because GI facilitates solutions to new problems does not mean that it originated as an adaptation to novelty. Having hands facilitates tool making, driving a car, throwing a spear, construction of shelters, and typing on a computer keyboard. All are novel usages, and having hands makes these novel usages possible, but we don't say that hands evolved as any form of adaptation to novelty. Instead, we understand that hands evolved to much more abstract and general, evolutionarily recurrent conditions which underlie all of these instances — ability to grasp objects and to manipulate them to adaptively useful ends. Similarly, having GI facilitates many new behaviors and solutions to new problems, but it also facilitates solutions to any challenging problem in which causality, event covariation, and similarity relations are present, not just so-called "novel" problems.

Along these lines, Kaufman et al. (2011) argue that Kanazawa's so-called novel problems are only one example of a broader category of problems, characterized by complexity and unpredictability. From my perspective, GI is applicable to any problem whose problem structure includes causality, predictive event covariation, or similarity relations, particularly when the problem or situation is "novel" (in details), complex, or unpredictable. As noted, novel problems have both recurrent, evolutionarily familiar elements — the abstract relational invariants (I_i) of causation (I_{ca}), covariation (I_{cov}), and similarity (I_{sim}) — as well as transient, evolutionarily nonrecurrent, novel details (n_i). Exploitation of the common relational invariants in problem structures makes the unpredictable novel elements in them much more predictable and less complex to the organism with GI. General improvisational intelligence makes the world more predictable because it is an adaptation to the former (I_i), not to the later (n_i), as prior theorists claim (e.g., Kanazawa, 2004, 2008, 2010, 2012). It is the exploitation of these evolutionarily familiar elements, recurrent across generations, that permits humans to innovate solutions to problems (such as those in Kanazawa's examples), which are "novel and nonrecurrent" in their details, but regular or invariant in their underlying phylogenetically recurrent, evolutionarily familiar relational structure.

General Improvisational Intelligence (GI) as Adaptive Specialization to Evolutionarily Familiar Relational Invariants Solves Cosmides and Tooby's "Enigma"

The major puzzle in Cosmides and Tooby's (2002) "enigma of human intelligence" is how mechanisms could evolve that are capable of solving adaptive problems that are local, transient (evolutionarily nonrecurrent), and novel (Barrett et al., 2007; Cosmides and Tooby, 2002). Note that by specifying the recurrent, "phylogenetically stable" (Barrett et al., 2007) conditions (I_i) that supplied the across-generation selection criteria for the evolution of GI, my *evolutionarily familiar relational invariants hypothesis* of the evolutionary origins of GI, unlike prior theories, solves Cosmides and Tooby's "enigma of human intelligence" (Barrett et al., 2007; Cosmides and Tooby, 2002; Kaufman, 2012). Resolving a long-standing theoretical puzzle in evolutionary psychology (Cosmides and Tooby, 2002; Kanazawa, 2004, Kaufman, 2012, Miller, 2000), my formulation (Figure 1) shows how the same mechanisms of natural selection which account for the evolution of domain-specific psychological adaptations (e.g., mechanisms for cheater detection, mate selection, etc.) also drove evolution of the problem-solving engines of GI.

This formulation also solves the "frame problem" (Tooby and Cosmides, 1992). From my perspective, the problem-solving mechanisms of GI are adaptive specializations to specific relational invariants recurrent over generations (and therefore captured by natural selection); the problems they solve are framed by the abstract relational invariants which they have genetically internalized, eliminating the problem of "combinatorial explosion" (Tooby and Cosmides, 1992), which has plagued prior theoretical attempts to place domain-general cognitive mechanisms within the same explanatory framework as the content-specific, adaptively specialized dedicated mechanisms of traditional evolutionary psychology.

The "Evolutionarily Familiar Relational Invariants Hypothesis" Predicts Prominent Features of Psychometric g which Prior Theories Cannot Explain

My *evolutionarily familiar relational invariants hypothesis* of the evolution of general improvisational intelligence (fluid intelligence; see Cattell, 1971, 1987; Kvist and Gustafsson, 2008) suggests several areas of potential unification between psychometric and evolutionary approaches to general intelligence which prior theories of the evolution of general intelligence fail to offer. My view that GI is a collection of adaptive specializations which have "genetically internalized" (Shepard, 1987a, 1992) evolutionarily familiar, abstract relations, explains Spearman's (1925, 1946) classic view that psychometric *g* corresponds to the "eduction" or drawing out "of relations and correlates." My formulation predicts that the "relations" referred to by Spearman should include cause–effect and similarity relations, while his "eduction" of "correlates" corresponds to an evolved disposition in humans (and many other species; e.g., see Chiappe and MacDonald, 2005; Güntürkün and Bugnyar, 2016; Kabadayi and Osvath, 2017; Wasserman, 1993b) to "draw out" adaptively important predictive event covariations in situations and problems (conditioning may be seen as a more rudimentary form of covariance detection not necessarily involving GI).[4] Developmental research supports this view.

Young children readily educe event covariations in new situations and problems and use these statistical regularities to quickly and accurately infer causal relations (Gelman and Legare, 2011; Gopnik, 2010; Gopnik and Wellman, 2012; Kaufman et al., 2011; Kushnir and Gopnik, 2007). Regarding similarity, Penn et al. (2008, p. 111) note that "numerous researchers have shown" that "the propensity to evaluate the similarity between states of affairs based on the causal–logical and structural characteristics of the underlying relations … appears quite early and spontaneously in all normal humans." Furthermore, my claim that GI includes the genetic internalization (Shepard, 1992; i.e., "evolutionary internalization," Shepard, 1994, p. 26) by natural selection of similarity, as an abstract, ubiquitous principle of the world, predicts an innate disposition of the mind to "expect" and to find similarities in the world, to group things by similarity into categories, to readily match new instances to the appropriate category based on similarity, and to infer properties of new instances of a category based on knowledge of properties of the category as a whole (i.e., generalization, categorization, categorical reasoning, categorically based inference, and categorical logic — these functions emerged as a family of related functional properties as natural selection fine-tuned the genetic internalization of similarity as a relational invariant in the world; on this basis, it is expected that these abilities should be correlated). These observations are reflected in "what William James (1890/1950) called 'the very keel and backbone of our thinking': sameness. The ability to evaluate … similarity … is clearly the sine qua non of biological cognition, subserving nearly every cognitive process from stimulus generalization and Pavlovian conditioning to object recognition, categorization, and inductive reasoning" (Penn et al., 2008, p. 111). "The ability to evaluate … similarity," regardless of the specifics of any particular example of similarity, is, on my view, a central feature of GI and is clearly one of the abstract relations educed in measures of *g*. It is noteworthy that metaphor and analogical reasoning are based in the capacity to find similarity in abstract relations such

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[4] Although Chiappe and MacDonald (2005) include conditioning as one of the components of general intelligence, Kaufman, DeYoung, Gray, Brown, and Mackintosh (2009) found that explicit voluntary memory for covariance is related to *g*, but automatic, implicit learning of covariance is not (Kaufman et al., 2010), suggesting that intelligence applies only to model-based learning but not model-free learning (DeYoung, 2017, personal communication).

as causality and categorical relations between domains (as in scientific models of hidden natural processes; e.g., the solar system model of electrons circling the atomic nucleus). Prior theories of the evolution of GI by Kanazawa and by Chiappe and MacDonald, as some form of adaptation to novelty, have little to say about these central properties of GI and psychometric *g*.

General intelligence and psychometric *g* are associated with ability for abstraction. Individual differences in performance on the Ravens Progressive Matrices, a test sensitive to ability "to induce abstract relations" (Carpenter, Just, and Shell, 1990), are highly correlated with *g* measured by traditional IQ tests such as the Wechsler. Moreover, higher IQ and ability for abstraction are both inversely correlated with cerebral glucose metabolic rate (Haier et al., 1988, Haier, Jung, Yeo, Head, and Alkire, 2004; Haier, Siegel, Tang, Abel, and Buchsbaum, 1992; Haier, White, and Alkire, 2003), suggesting an efficiency model of individual differences in *g* in which superior ability for abstraction increases processing efficiency.[5] Prior theories by Kanazawa and by Chiappe and MacDonald cannot explain these associations. By contrast, according to the present formulation, because the selection criteria which drove the evolution of the problem-solving engines of GI are themselves abstract and relational, and because these mechanisms evolved as genetic internalizations of abstract relational invariants, GI/*g* should inevitably have abstraction as one of its central distinguishing features. It is noteworthy that Penn et al. (2008) find that one of the primary factors that distinguishes human cognition from that found in other species is human ability for high levels of abstraction in similarity and causal relations, a finding predictable from my formulation, but one unanticipated and without explanation in prior theories of the evolutionary origins of GI as some form of adaptation to novelty (e.g., Chiappe and MacDonald, 2005; Kanazawa, 2004, 2010).

Evolutionary Improvements in Human General Intelligence Versus Evolutionary Origins

Although migration to colder climates (Kanazawa, 2012), the appearance of large and complex human social groups (Byrne and Whiten, 1988; Gottfredson, 1997; Kaufman et al., 2011; MacLean, Merritt, and Brannon, 2008), rapid fluctuations in climate (Chiappe and MacDonald, 2005), or other extraordinary adaptive challenges may have catalyzed the evolution of the effectiveness and power of human GI, nevertheless GI itself would have had much earlier and more ordinary evolutionary origins. Similarity, causality, and predictive event covariation were

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[5] However, one notable exception is that during cognitively difficult tasks psychometric *g* becomes positively correlated with neural activity suggesting that persons higher in *g* may be better able to recruit mechanisms that process abstract relational invariants, permitting formation of new abstract models that increase problem solving effectiveness and efficiency over the long haul; DeYoung, personal communication, 2017; but see Poldrack, 2015, for a critique of the explanatory utility of the concept of efficiency in neuroscience.

always present and always highly adaptively significant, in all environments, not just under extraordinary conditions such as those listed above. If early humans were able to successfully adapt to the colder climates to which they migrated (Kanazawa, 2012), or to rapid fluctuations in climate or other climatic sources of novelty (Chiappe and MacDonald, 2005), and if this outcome depended upon general intelligence as many theorists claim (e.g., Chiappe and MacDonald, 2005; Kanazawa, 2012), then the mechanisms of GI must have already been in place by the time these challenges began. If so, these extraordinary conditions cannot be the evolutionary origin of GI. Instead, on my view, GI had its evolutionary origins very early on, as natural selection favored genes which internalized the abstract relational invariants I have described in this article; furthermore, their early and universal presence in the world combined with their potent adaptive significance must have forged the evolution of GI in multiple ancestral lines under conditions which were not unique to human ancestors. This hypothesis is supported by evidence that GI exists in a wide range of species including apes, dogs, corvid birds, and even some marine invertebrates, suggesting that it evolved multiple times in diverse lineages (Arden and Adams, 2016; Chiappe and MacDonald, 2005; Deaner, Van Schaik, and Johnson, 2006; Güntürkün and Bugnyar, 2016; Kabadayi and Osvath, 2017; Lefebvre, Reader, and Sol, 2013; Reader, Hager, and Laland, 2011). This line of reasoning strongly suggests that the conditions for its original evolution were not unique to the hominid line and did not require conditions of extraordinary novelty (e.g., migration to cold climates or other conditions listed above) as most theories assume. Once these mechanisms of general intelligence were already in place, then any environmental conditions which taxed abilities to exploit abstract, relational properties of the world to solve problems would have driven evolution of increases in the efficiency and effectiveness of GI (by evolved increases in capacities for abstraction; see below). This view is consistent with Kaufman et al. (2011) who see novelty as only one special case of a broader set of conditions of complexity and unpredictability that would spur evolution of GI. They state:

> Increased social group size and rapidly increasing cultural complexity are likely to have rendered pre-existing heuristic adaptations increasingly fallible in human ancestors, thus increasing the selection pressure on domain-general mechanisms that could logically analyze the causal structure of situations even when it was too complex to be adequately processed by modular heuristics. . . . In the case of complex, unpredictable situations, regardless of their superficial dissimilarity, selection for increased ability to analyze causal structure is highly likely. (p. 313)

Greater ability for abstraction of the relational invariants of causality, covariation, and similarity would have permitted recognition of higher-order patterns and the creation of higher-order predictive models based upon them, thereby decreasing unpredictability and ordering complexities, making them more cognitively and adaptively manageable. With ability for higher orders of abstraction, patterns not apparent at lower levels of abstraction would emerge and could be put to adaptive use. Events or problems which would be otherwise too unpredictable or impossibly complex would become more predictable and less complex to a mind so equipped (see Clark, 2013 for discussion of the "predictive brain"). Under these circumstances, with increased social group size and rapidly increasing cultural complexity in early humans (see above; Kaufman et al., 2011, p. 313), adaptive payoffs of a large cerebral cortex, capable of high levels of abstraction of relational invariants, may have been sufficient to overcome the energy costs and risks of childbirth associated with larger brain size. Despite the ecological ubiquity of the abstract relational invariants described in this paper, and the consequent evolution of the mechanisms of GI in multiple lineages, the unique degrees of complexity for early humans described above by Kaufman et al. (2011) could have driven the evolution of increasing abilities for abstraction of the relational invariants described herein, giving human GI its exceptional powers for creativity, improvisation, and adaptive plasticity to a wide range of environments.

Higher-Order Abstraction and Human General Intelligence

This reasoning suggests that ability for high levels of abstraction in causal and similarity relations (Penn et al., 2008) and in covariation detection (Wasserman, 1993b) may be central to the phylogenetically unprecedented achievements of the human intellect.[6] In a review of the comparative literature, Penn et al. (2008) find "no compelling evidence" that any nonhuman animal can reason about the "relation between relations," something that humans do readily. Neither do they find convincing evidence for analogical reasoning (dependent upon judgments of abstract similarities across domains) in nonhuman animals. Consistent with Penn et al. (2008), Walker and Gopnik (2014) report that although human toddlers readily detect abstract relational causality quickly with only a few training trials, non-human primates have great difficulty with similar tasks even after hundreds of trials.[7] Penn et al. (2008, p. 123) believe that what distinguishes human cognition from that in non-human animals is "the ability to reason about higher-order relations," and that this capacity for high levels of abstraction "subserves a wide variety of distinctively human capabilities."

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[6] Furthermore, differences among humans in ability for abstraction of these relations may account, at least in part, for individual differences in psychometric *g*, perhaps explaining the high correlations between *g* and performance on Raven Progressive Matrices, both associated with abilities for abstraction.

[7] Gopnik et al. (2001, p. 627) point out that "causal learning mechanisms are an interesting halfway point between domain-general and domain-specific mechanisms.... Unlike the usual domain-specific mechanisms, causal inference procedures can be applied to input from many domains … but [are] more constrained than traditional domain-general learning mechanisms." Similarly, Barrett and Kurzban (2006) argue that even so-called domain-general mechanisms have "formal input criteria."

Research in molecular genetics suggests one possible explanation for how human ability for high levels of abstraction may have come about. Pollard (2009), comparing human and chimpanzee genomes, found “massive mutations” in humans in the “DNA switches” controlling size and complexity of cerebral cortex, extending the period of prenatal cell division in human cerebral cortex by several days compared to our closest primate relatives. Research using artificial neural networks suggests that increasing cortical complexity leads to sudden leaps in ability for abstraction and rule-like understanding of general principles (Clark, 1993). Findings by Penn et al. (2008) strongly suggest that superior ability for abstraction of relational information may be the key component explaining differences in general intelligence between humans and nonhuman animals. These abilities may involve anterior dorsolateral prefrontal cortex in humans (Kroger et al., 2002; Reber, Stark, and Squire, 1998).

Unification of Traditional “Dedicated” Intelligences and General Improvisational Intelligence within a Common Darwinian Framework

The above formulation unifies evolutionary psychology by showing *how* GI (which has been heretofore so problematic for evolutionary psychology; e.g., Barrett et al., 2007; Cosmides and Tooby, 2002; Kanazawa, 2004; Kaufman, 2012; Miller, 2000) originated from the same dynamics of Darwinian natural selection that fashioned the domain-specific “dedicated” intelligences (e.g., modules for mate selection, language acquisition, predator avoidance, TOM, etc.; Buss, 2008; Cosmides and Tooby, 2002). Kanazawa (2010) claims that the critical distinction between these two categories of adaptively specialized mechanisms is that the dedicated mechanisms evolved for evolutionarily familiar problems which were anticipated by evolution, while, by contrast, the mechanisms of GI evolved for evolutionarily novel nonrecurrent problems which were unanticipated by evolution. However, by the analysis I present above, all adaptive problems, including Kanazawa’s “evolutionarily novel problems” are in fact evolutionarily familiar and “anticipated by evolution.” If this were not the case, the mechanisms of GI could not have evolved (Barrett et al., 2007). The actual difference between the traditionally defined “dedicated intelligences” and the problem-solving engines of GI lies only in the higher degrees of abstraction, and wider ecological distribution, of the regularities which served as the selection criteria for the mechanisms of GI compared to those which drove the evolution of the traditional dedicated mechanisms. Kaufman et al. (2011) make a related point. They state:

> Evolutionary psychologists sometimes argue that a class of situations must be relatively narrow to exert consistent selection pressure, but this claim is insufficiently justified. Any regularity in the environment can exert selection pressure if it poses a challenge or an opportunity to the organism.... (p. 313)

In the case of the abstract relational invariants which drove the evolution of GI, the adaptive opportunity is difficult to overstate. Genetic internalization of causality, covariation, and similarity relations provides the mind with innate implicit "knowledge" about abstract relational properties of the world which can be put to work to solve adaptive problems of near endless variety. This provides the mind with what Pinker (2007) referred to as the "infinite use of finite means," clearly a distinguishing, even diagnostic, property of human GI and its improvisational creativity.

Problem Solving in Imagination Utilizes Innate Knowledge of Causality, Predictive Covariation, and Similarity as Abstract Principles of How the World Works

The use of imagination to solve adaptive problems may be an additional key component of human GI. This would entail use of visual imagery, constrained by these same adaptive specializations of GI to generate and review in imagination possible future behaviors and their probable outcomes before committing to action in the physical world. Thus, even in the "mind's eye," these same principles of similarity, covariation, and causality dictate the possibilities. Imaging (imagining) one's self in action and "seeing" probable outcomes in the world, based on mental projections from innate knowledge of the abstract principles of causality, similarity, and predictive event covariation, would provide means for vicarious mental testing of behavioral options before committing to those actions in the physical world, and would therefore be an essential component in the planning of future adaptive action. Much of what we call "thought" may be of this form.

This component of GI may involve construction of visual-like mental images in regions of visual and motor cortex (Kanwisher, 2009; Roth et al., 1996; Wraga, Thompson, Alpert, and Kosslyn, 2003) which may have been co-opted (Gould and Vrba, 1982) into this "visualization" function. Consistent with this hypothesis, brain imaging studies show that when humans imagine a particular movement, the same brain region that becomes active during the actual movement also becomes active during the imagined movement, even though no actual movement occurs. In both cases, the activated brain area shows nearly the same fMRI image (Ganis, Thompson, and Kosslyn, 2004; Kanwisher, 2009; Kosslyn, Thompson, and Ganis, 2006). Mental testing of planned actions in the mind's eye (using innate, implicit "knowledge" of cause–effect, predictive event covariation, and similarity relations) is not only safer and faster for the organism, but is also enormously efficient in terms of caloric expenditure — three factors which would have created strong selection pressure for evolution of imagination and which may have helped offset energy costs associated with an enlarged cerebral cortex. This suggests that imagination may be an evolved psychological adaptation (or perhaps, alternatively, an "exaptation;" Gould and Vrba, 1982) vital to the power of human GI and to the ability to accurately project oneself — one's behavior and its probable effects — into future time, permitting long-term goals, and the accurate ("realistic") mental imaging of the means by which to achieve them. Significantly, visual imagery in the mind's eye can also be employed to mentally test novel combinations of causes and effects, similarity relations, and predictive covariations to discover new knowledge about hidden causes (Penn et al., 2008), eventually leading to the creation of sophisticated scientific models of how the world works — human GI at its best.

The emergence of this co-opted "visualization" ability may help account for the development of modern human cognition, first appearing some 60,000–100,000 years ago (Mellars, 2005). Speculatively, superior abilities for imagination of the type described above might account, at least in part, for human competitive advantage over Neanderthals perhaps contributing to Neanderthal extinction about 30,000 years ago (Watson and Berry, 2009). Consistent with this view, morphological studies suggest enhanced parietal lobe development in modern humans compared to Neanderthals (Bruner, 2010; by contrast, recent studies show little relative enlargement of the frontal lobes in humans compared to apes; see Barton and Venditti, 2013) and fMRI studies implicate parietal cortex in the use of imagination (Nair, Purcott, Fuchs, Steinberg, and Kelso, 2003). Bruner (2010, p. S84) suggests that "the parietal lobe system 'forms a neural image of surrounding space' (Mountcastle, 1995 p. 389)," and perhaps of one's potential future action in that space. Significantly, parietal cortex has strong linkages with prefrontal cortex forming a frontoparietal network: the inferior parietal lobule is primarily connected with dorsolateral prefrontal cortex (Bruner, 2010), associated, in part, with abilities for abstract thought, while upper parietal regions, according to Bruner (p. S85), are associated in the literature with functions such as abstract representation, internal mental images, "imagined world[s]," and "thought experiment" (i.e., imagination).

The proposition that mental imaging of possible future actions and their probable outcomes, and imaging of new combinations of causes and effects, as a property of GI is also supported by evidence from psychometrics. This imaging ability is most likely measured by the psychometricians' *broad visual perception factor* (Gv), "which is an ability to generate, retain, retrieve and transform visual images" (Kvist and Gustafsson, 2008, p. 423), one of the sub-factors of *g* in Carroll's (1993) widely accepted three-stratum hierarchical model of human intelligence, thus suggesting one possible adaptive function of Gv. This formulation again identifies linkages between psychometrics and an evolutionary approach to the origins and structure of GI that other theories which claim that general intelligence is an adaptation to novelty have not discovered and cannot explain.

Some animals may also use imagination (mental imaging) to solve novel problems (Emery and Clayton, 2004; Klein, Robertson, and Delton, 2010). For example, Heinrich (2000; see Chiappe and MacDonald, 2005) reports the use of insight by ravens to solve new problems. The apparent use of insight by chimpanzees to solve novel problems in Köhler's classic experiments is well known. It is likely that even in these animals, implicit understanding of causality, similarity, and predictive event covariation guide imagination. The adaptive benefits which arise from the use of visual-like imagery to imagine in the mind's eye possible cause–effect combinations and possible future behavioral options and their likely outcomes suggest one adaptive function of consciousness and may provide clues about its evolutionary origins.

Abstract Relational Invariants and Evolution

For some readers, abstract relational invariants such as causality or similarity may appear too ethereal, too abstract, to be captured by natural selection. However, by its very dynamics, natural selection is an abstracting process. Because it operates over generations, natural selection can only capture across-generation regularities or invariants which are "abstracted away" or "distilled" from case-specific instances of the regularity (principle of distilled invariants; Figure 1). Although these instances vary in their case-specific "surface" details (n_i), they share a common underlying structure. It is this abstracted common structure (I_i) that is captured by natural selection. Moreover, natural selection is very resourceful and opportunistic, capable of engineering adaptations of seemingly impossible complexity and functional effectiveness such as the human eye, the immune system, or mechanisms of the human mind capable of deriving general laws of nature that form the basis for the modern scientific worldview (Dawkins, 1976; Mayr, 1970). As Tooby and Cosmides (1992, p. 48) state: "No instance of anything is intrinsically (much less exclusively) either 'general' or 'particular' — these are simply different levels at which any given system of categorization encounters the same world.... Selection operated across ancestral hominid populations according to what were, in effect, systems of categorization, screening ... variability for any recurrent relationships that were relevant to the solution of adaptive problems." Clearly, evolutionarily recurrent abstract, relational invariants (I_i) inherent in the structure of the world such as causality, similarity, and event covariation were always highly "relevant to the solution of adaptive problems" in humans (and in many other species which also appear to possess the mechanisms of GI; Chiappe and MacDonald, 2005; Deaner et al., 2006; Deaner, Isler, Burkart, and Van Schaik, 2007; Emery and Clayton, 2004).

Principles of the Mind and Regularities of the World

The present formulation builds upon the seminal work of Shepard (1987a, 1987b, 1992, 1994, 2001) who observed that natural selection has evolved "a mesh between principles of the mind and regularities of the world" (1987a, p. 251). According to Shepard (1992, p. 500) "all niches …, though differing in numerous details, share some general — perhaps even universal — properties." He argues that "natural selection must have favored genes not only on the basis of how well they propagated under the special circumstances peculiar to the ecological niche currently occupied, but also,… even more consistently in the long run, according to how well they propagate under the general circumstances common to all ecological niches" (1992, p. 500) According to my formulation, these "circumstances common to all ecological niches" include the abstract relational invariants (I_i) of causality, predictive event covariation, and similarity, explaining the evolutionary origins of the problem-solving mechanisms of GI. Consistent with this claim, Shepard (1994, p. 26) states, "The principles that have been most deeply internalized [into the mind] may reflect quite abstract features of the world" and, furthermore, that "invariant laws require formulation in terms of more abstract regularities in the world" (2001, p. 588). Accordingly, over the course of evolution, the genetic internalization by natural selection of abstract relational invariants (I_i) such as causality, event covariation, and similarity is not only to be expected (Figure 1; principle of distilled invariants), but on my view, is inevitable (suggesting the likelihood that intelligence exists elsewhere in the universe and that it evolved by similar evolutionary dynamics with identifiably similar results).

Understanding of Abstract Relations is the Sine Qua Non of Human Intelligence

This formulation is supported by the work of Gopnik and her colleagues on "theory theory" (Gopnik and Sobel, 2000, p. 1205), which shows that from an early age children implicitly understand and readily use abstract principles to solve new problems (Gopnik and Wellman, 2012; Walker and Gopnik, 2014), and by Penn et al. (2008), who, as noted above, find that the use of causal principles and similarity assessments of high degrees of abstraction is a distinguishing feature of human cognition and problem solving. As they state: "Even preschool-age children understand that the relation between a bird and its nest is similar to the relation between a dog and its doghouse despite the fact that there is little 'surface' or 'object' similarity between the relations' constituents" (p. 111). Along similar lines, very young children also show the predisposition to readily attend to and to learn details of the cause–effect relations among the specific events they encounter in their environments (e.g., see Gopnik, 2010; Walker and Gopnik, 2014), providing the innate groundwork for later cause–effect analyses by adults, eventually leading to a sophisticated understanding of the world and its hidden causal principles (Penn et al., 2008; Walker and Gopnik, 2014).

The formulation presented in this paper provides an explanation of the evolutionary origins of GI which is consistent with prevailing adaptationist interpretations of evolutionary mechanisms (Barrett et al., 2007; Cosmides and Tooby, 2002; Ermer et al., 2007; Gallistel, 1992, 1995; Miller, 2000), while the evolutionary theories of Chiappe and MacDonald (2005) and Kanazawa (2004, 2010, 2012) violate the fundamental logic of modern evolutionary theory. Accordingly, GI is not an adaptation to evolutionary or environmental novelty as generally assumed, but instead it is a collection of adaptive specializations to the ubiquitous, evolutionarily familiar, across-generation, abstract relational invariants of the world, continuously present from the first appearance of life on earth and before. On this view, general fluid "improvisational" intelligence provides another example, heretofore unrecognized, of Shepard's elegant observation that there has evolved "a mesh between principles of the mind and regularities of the world."

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