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Analogical mapping across sensory modalities and evidence for a general analogy factor

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ABSTRACT

Analogy is a central component of human cognition. Analogical "mapping" of similarities between pieces of information present in our experiences supports cognitive and social development, classroom learning, and creative insights and innovation. To date, analogical mapping has primarily been studied *within* separate modalities of information (e.g., verbal analogies between words, visuo-spatial analogies between objects). However, human experience, in development and adulthood, includes highly variegated information (e.g., words, sounds, objects) received via multiple sensory and information-processing pathways (e.g., visual vs. auditory pathways). Whereas cross-modal correspondences (e.g., between pitch and height) have been observed, the correspondences were between individual items, rather than between relations. Thus, analogical mapping (characterized by second-order relations between relations) has not been directly tested as a basis for cross-modal correspondence. Here, we devised novel cross-modality analogical stimuli (lines-to-sounds, lines-to-words, words-to-sounds) that explicated second-order comparisons between relations. In four samples across three studies–participants demonstrated well-above-chance identification of cross-modal second-order relations, providing robust evidence of analogy across modalities. Further, performance across all analogy types was explained by a single factor, indicating a modality-general analogical ability (i.e., an "analo-g" factor). Analo-g explained performance over-and-above fluid intelligence as well as verbal and spatial abilities, though a stronger relationship to verbal than visuo-spatial ability emerged, consistent with verbal/semantic contributions to analogy. The present data suggests novel questions about our ability to find/learn second-order relations among the diverse information sources that populate human experience, and about cross-modal human and AI analogical mapping in developmental, educational, and creative contexts.

1. Introduction

Identifying similarities that meaningfully connect a person's varying experiences is fundamental to human learning in developmental, social, and educational contexts, and to creative insights that advance art, science, and industry (Dunbar & Blanchette, 2001; Gelman, Raman, & Gentner, 2009; Gentner, 1983; Gentner & Markman, 1997; Green, 2016; Green et al., 2017, 2014; Green, Kraemer, Fugelsang, Gray, & Dunbar, 2010; Holyoak, 2012; Knowlton, Morrison, Hummel, & Holyoak, 2012; Weinberger, Iyer, & Green, 2016). Analogical mapping, which is characterized by detecting similar relationships between the elements of separate items or experiences (i.e., second-order relations between relations), often enables understanding of abstract similarities (Bunge, Wendelken, Badre, & Wagner, 2005; Gentner, 1983; Green, 2016; Hummel & Holyoak, 1997; Knowlton et al., 2012; Knowlton & Holyoak, 2009; Krawczyk, 2012). Analogy has thus far been primarily studied *within* modalities of information (e.g., verbal analogies between words, visuo-spatial analogies between objects). By contrast, real-world experiences, in development and throughout life, present multiple simultaneous stimulus modalities (e.g., words, sounds, objects) received via distinct sensory and information-processing pathways (e.g., visual vs. auditory pathways). Questions remain about the extent to which

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analogical mapping can connect information received via different sensory and information-processing streams. In particular, the extent to which individuals can identify second-order relations across modalities – relations not just between stimuli, but between the relations of stimuli to each other – remains unclear. Addressing this question is necessary to determining the scope of our analogical capacity to integrate the diverse information present in our experience.

Prior work indicates that people are able to identify correspondences between stimuli in different sensory modalities. For example, research on "crossmodal correspondence" (Spence, 2011), has shown matching of stimulus intensities across modalities (e.g., volume and brightness; Stevens & Marks, 1965) and that high-pitched tones are associated with shapes arrayed higher in a visual field (Marks, 1987). Subsequent work has demonstrated further instances of correspondence between auditory stimuli and visual/spatial stimuli (Dolscheid, Hunnius, Casasanto, & Majid, 2014; Dolscheid, Shayan, Majid, & Casasanto, 2013; Mix, Huttenlocher, & Levine, 1996). Other work has shown cross-modal connections between colors and odors (Spence, 2020) and tastes and sounds (Crisinel & Spence, 2010). There is also clear evidence of sound symbolism in linguistics; prior work has revealed cross-modal mappings between phonemes, pitch, and size (Thompson & Estes, 2011) as well as associations between emotional valence and phoneme location within a word (Adelman, Estes, & Cossu, 2018). Sound symbolism has been observed across human languages (Adelman et al., 2018) and in non-linguistic psychological tasks (Dolscheid et al., 2013), suggesting it may function as a biologically-based bootstrapping phenomenon to convey spatial representational information (Imai & Kita, 2014). Even infants who have not yet acquired language exhibit sensitivity to the correspondence between pitch and space (Dolscheid et al., 2014). Related work examining cross-modal metaphor has identified stimuli of different modalities that evoke or refer to shared conceptual themes/associates (e.g., scary images paired with scary sounds, or music and images that evoke pride; Forceville & Urios-Aparisi, 2009).

Cross-modal research has thus far focused on comparisons between individual stimuli in different modalities, rather than comparing relations between stimuli. Thus, an unresolved question is whether cross-modal correspondences are understood by formulating analogies (i.e., second-order relations between relations) or via mechanisms proposed for metaphoric mapping that do not require second-order relations. In particular, the prior literature on metaphor (which compare individual items or concepts without explicitly comparing relations) reflects substantial debate concerning whether and when metaphors may be understood via analogy or via categorization-based mechanisms. It appears that, in at least some instances, metaphors are understood via "one shot" categorical associations (Kintsch, 2000) between a source and a target without the explicit alignment and mappings of second-order relations that characterize analogy (for review, see Holyoak & Stamenković, 2018). For example, cross-modal correspondences may stem from shared association with an object/entity (e.g., a barking sound and an image of a dog), descriptive terminology (e.g., "high" and "low" can apply to sounds and locations), and more experiential categories like pleasantness (e.g., a sweet taste and a soothing sound, or a high note evoking the sensation of being high in the air; Forceville & Urios-Aparisi, 2009; Spence, 2011).

Even if one takes the position that all metaphors can, with sufficient deliberate effort, be deconstructed to identify the constituent elements of analogies, this does not necessarily imply that a person actually goes through the process of mapping a specific second-order relation each time they understand a metaphor. For at least some metaphors, it may be that deeply ingrained spatial representations of non-spatial concepts (e.g., as posited above for pitch and spatial extent; Casasanto & Boroditsky, 2008; Dolscheid et al., 2013, 2013; Imai & Kita, 2014; Lakoff & Johnson, 2008) afford a basis for metaphoric mapping. If the physically extended nature of space corresponds to a model of pitch as continuum of physical height or thickness, this might afford a basis for pitch-space metaphors to be meaningful (e.g., a high note corresponds to a physically high point) but does not—in and of itself—require a reasoner to identify a specific second-order relation for any particular instance of a space-pitch metaphor (i.e., between a specific spatial relation and a specific tonal relation). Similar questions apply to familiar metaphors between space and time or amount (e.g., Boroditsky & Ramscar, 2002; Casasanto & Boroditsky, 2008; Lakoff & Johnson, 2008), and it is also less clear whether those metaphors represent connections between separate modalities (e.g., what is the non-spatial modality of time)? In any case, they do not appear to cross boundaries of *sensory* modality.

To address this issue, the present study investigated cross-modal *second-order* relations. The stimuli in the present study were devised to directly compare one explicit first-order relation (in one modality) to another explicit first-order relation (in a separate modality), such that the mapping between these first-order relations was based on an explicit second-order relation. In particular, we employed a novel set of cross-modal analogies using the classic 4-term (A:B::C:D) form. Though limited in several ways with respect to ecological validity, this form of analogy has the advantage of making the second-order mapping explicit (rather than implied).

Extant analogy research *within* each of several modalities points to the additional question of whether analogical ability is modality-general. Is there an underlying analogical ability factor that supports performance independent of modality (i.e., an "analo-*g*" factor)? Neuroimaging evidence indicates substantial overlap in neural activity associated with analogical reasoning in verbal and visuo-spatial modalities respectively (Cho et al., 2009; Knowlton et al., 2012; Knowlton & Holyoak, 2009). This suggests the possibility of neurocognitive mechanisms that support analogy in a modality-general way, although there is also clear evidence of modality specificity (Hobeika, Diard-Detoeuf, Garcin, Levy, & Volle, 2016).

If analo-*g* does exist, what other cognitive factors predict it? Previous psychometric work has found correlations among analogical performance in several modalities (i.e., further suggesting a modality-general factor; Snow, Kyllonen, & Marshalek, 1984), which has been attributed to shared relationships with fluid intelligence, and specifically Raven's Progressive Matrices (RPM; Raven & Raven, 1998). Though fluid intelligence appears strongly related to analogy, and though RPM involves analogical relations, this does not entail that fluid intelligence (or RPM specifically) fully represents the processes that support analogy. Likewise, while working memory supports analogy (e.g., Simms, Frausel, & Richland, 2018; Viskontas, Morrison, Holyoak, Hummel, & Knowlton, 2004), analogical capacity appears to reflect more than working memory capacity alone (Richland & Morrison, 2010). RPM is a visuo-spatial task, so it may not capture language/verbal processes that are proposed to support analogical reasoning (e.g., Gelman et al., 2009; Gentner & Forbus, 2011; Gentner & Markman, 2006; Holyoak & Thagard, 1989; Hummel & Holyoak, 1997). Indeed, vocabulary knowledge is a robust predictor of verbal analogical reasoning (Jones & Estes, 2015). The presence of a modality-general analogical ability factor–and the relationship of such a factor to RPM–should thus be tested. Testing the association of a putative analo-*g* with visuo-spatial vs. verbal ability would further help determine the nature of such a factor, particularly with respect to models of reasoning that emphasize verbal/semantic processes (Braine & O'Brien, 1998; Rips, 1994) vs. visuo-spatial processes (Goodwin & Johnson-Laird, 2005). Additionally, extant correlational work has not tested correlations between analogies that differ with respect to sensory modality (e.g., auditory vs. visual), and indeed has included only visual–not auditory–information.

To address these questions, we tested the hypotheses 1) that analogical similarity can be mapped between different informational and sensory modalities, and 2) that analogical ability is modality-general; that is, we tested for the presence of a modality-general "analo-*g*" factor. Further tests addressed the relationships of verbal ability, visuo-spatial ability, and fluid intelligence to analogical mapping within and across modalities.

2. Analogical reasoning task

We developed five types of analogy stimuli (Fig. 1), including two within-modality types (lines-to-lines; words-to-words), and three novel cross-modality stimulus types (lines-to-sounds; lines-to-words; and words-to-sounds). The task used a frequently-employed analogical verification format (e.g., Dunbar & Blanchette, 2001; Gentner & Markman, 2006; Green, 2016), which asks participants to make binary true-false judgements about whether the relation conveyed in the first pair (i.e., A:B) is analogous to the relation conveyed in the second pair (C:D). While this form of analogical reasoning is fairly simple relative to more complex forms of analogical problem-solving, learning, and decision-making that characterize real-word experience, the simplified A:B::C:D format is conducive to uniform presentation of larger numbers of stimuli and, as noted above with respect to the objective of the present work, makes second-order analogical relations explicit (rather than implied).

3. Study 1

3.1. Method

The primary objective of Study 1 was a first-time assessment of analogical mapping across modalities (i.e., an initial proof-of-concept test). Independent samples were collected online and in-person. All samples–within all studies–provided at least 80% power to detect medium effects at Bonferroni-corrected $\alpha = 0.05$ (Champely, 2009).

3.1.1. Online sample

Participants ($N = 71$, $M_{age} = 29.8$, 53.5% female; see SI for additional details regarding quality control for all online samples) were recruited online using Amazon Mechanical Turk. All participants completed five types of trials: words-to-words (45 trials; 30 True), lines-to-lines (51 trials; 34 True), lines-to-words (51 trials; 36 True), lines-to-sounds (47 trials; 34 True), and words-to-sounds (53 trials; 38 True). Following each trial, participants received accuracy feedback (correct or incorrect response).

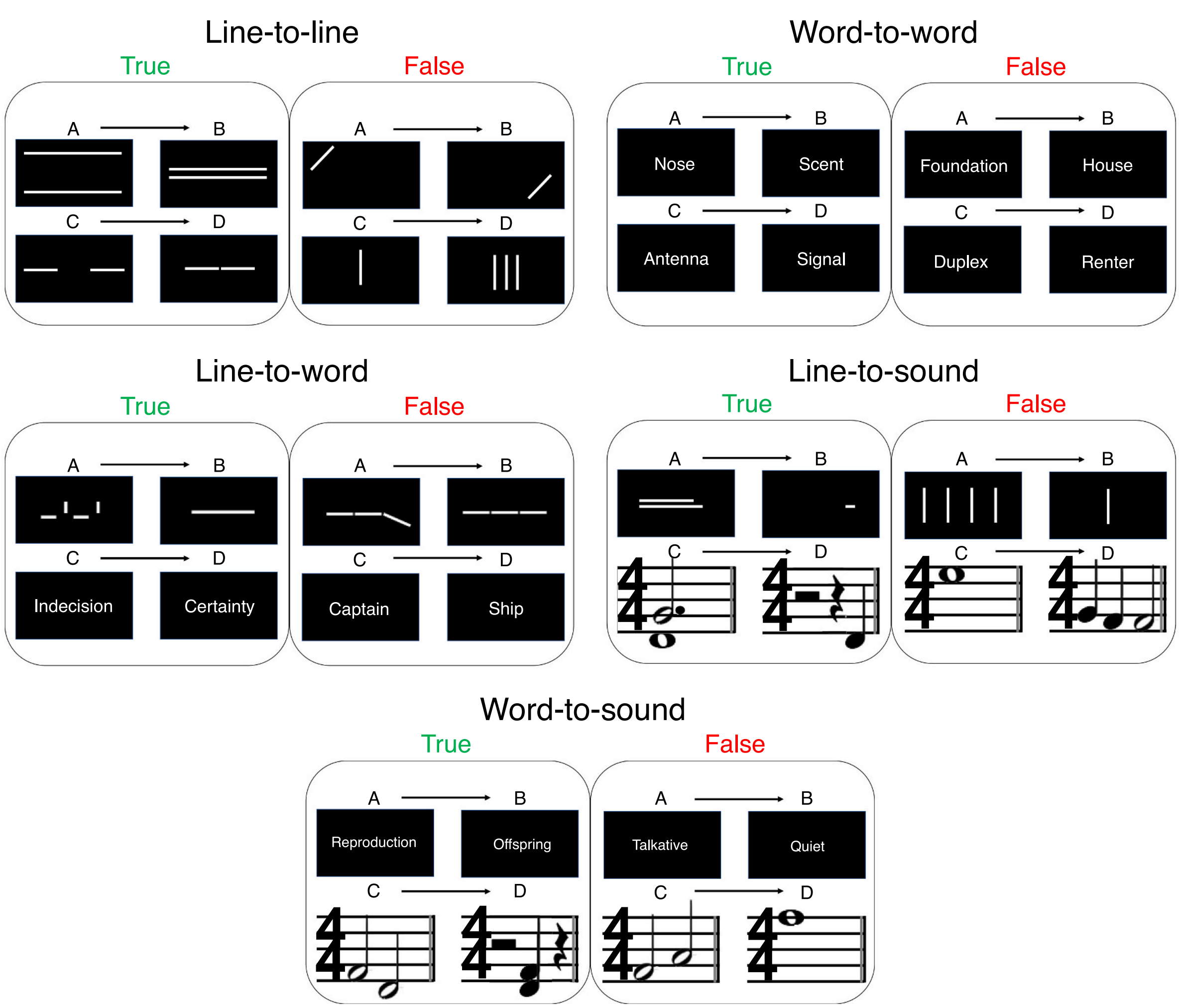

Fig. 1. Example within-modality and cross-modality analogy trials. All analogy trials were of the form, “A is to B as C is to D.” Participants were instructed to indicate by button press whether each analogy was True or False. For example, in the True lines-to-sounds trial depicted in the figure, both the line analog (A-B) and sound analog (CD) were devised to convey the relation of paired elements (A: paired visual elements of an image; C: paired notes of a two-note chord) to a feature that differentiates those paired elements (B: the differentiating quantity of length of the longer line; D: the differentiating quantity of duration of the longer note). The True words-to-sounds example was devised to convey a relation of two temporally adjoined half notes (C) to a quarter note that combines them equally (D), as “reproduction,” often involving physical adjoinment (A), results in an “offspring” (B) combining two parents' genes equally. For analogies involving sounds, participants heard tones—no musical notations/symbols were presented. All stimuli are available at https://osf.io/6kh98/.

3.1.2. In-person sample

A separate group of 49 adults reporting no history of psychoactive drug use or psychiatric diagnosis (M_{age} = 22.37; 59.2% female) completed words-to-words, lines-to-lines, lines-to-words, and lines-to-sounds trials without feedback.

3.2. Results

Statistical analyses were performed separately for the two samples because of differences in experimental procedures (e.g., feedback provided in the online sample). Trials that were outliers for accuracy in both samples (SI) were removed from analyses in Study 1 and excluded from the stimulus set presented in Studies 2 and 3.

3.2.1. Online sample

Accuracy was high for within-modality (words-to-words: M = 76.3%, 95% CI [72.5%–80.1%]; lines-to-lines: M = 72.0%, 95% CI [69.1%–74.8%]) and, critically, cross-modality (lines-to-words: M = 70.8%, 95% CI [67.6%–74.1%]; lines-to-sounds: M = 74.8%, 95% CI [70.7%–78.9%]; words-to-sounds: M = 72.4%, 95% CI [68.5%–76.3%]) trials, and significantly above chance (50%) for all trial types (all $p < 0.0001_{\text{Bonferroni-corrected}}$, $d > 1.37$). To afford greater discriminability and mitigate ceiling effects given high accuracy scores for all analogy types, we employed a signal detection index (d-prime; Macmillan & Creelman, 2004), calculated as the difference between the standardized hit rate (correct identification of valid analogies) and standardized false alarm rate (incorrectly endorsing invalid analogies). d-prime scores were significantly above chance for within-modality and, critically, cross-modality analogies (lines-to-lines and lines-to-sounds: $p < 0.05_{\text{Bonferroni-corrected}}$, $d > 0.30$; all others $p < 0.0001_{\text{Bonferroni-corrected}}$, $d > 0.58$; Fig. 2). Notably, performance for line-to-line analogies was nominally lower than performance on all three cross-modal analogies, suggesting that cross-modal analogies were not uniformly more challenging than within-modal analogies.

Finally, we identified six trials (2 lines-to-words, 2 words-to-sounds, 1 lines-to-lines, 1 words-to-words, 0 lines-to-sounds) with outlyingly low accuracy (accuracy>2 SD below the mean; SI).

3.2.2. In-person sample

Accuracy was again high for within-modality (words-to-words: M = 88.6%, 95% CI [86.0%–91.2%]; lines-to-lines: M = 84.4%, 95% CI [82.4%–86.5%]) and, critically, cross-modality (lines-to-words: M = 83.6%, 95% CI [81.2%–85.3%]; lines-to-sounds: M = 88.2%, 95% CI [86.0%–90.5%]) trials, and significantly above chance (50%) for all trial types for both percent correct and d-prime (all $p < 0.0001_{\text{Bonferroni-corrected}}$, $d > 3.17$,). All six outlying items in the online sample were also outliers in the in-person sample. Taken together, both Study 1 samples provided robust proof-of-concept that analogical similarity in the form of explicit second-order relations can be mapped across modalities, including mapping between stimuli presented in different sensory modalities (visual vs. auditory).

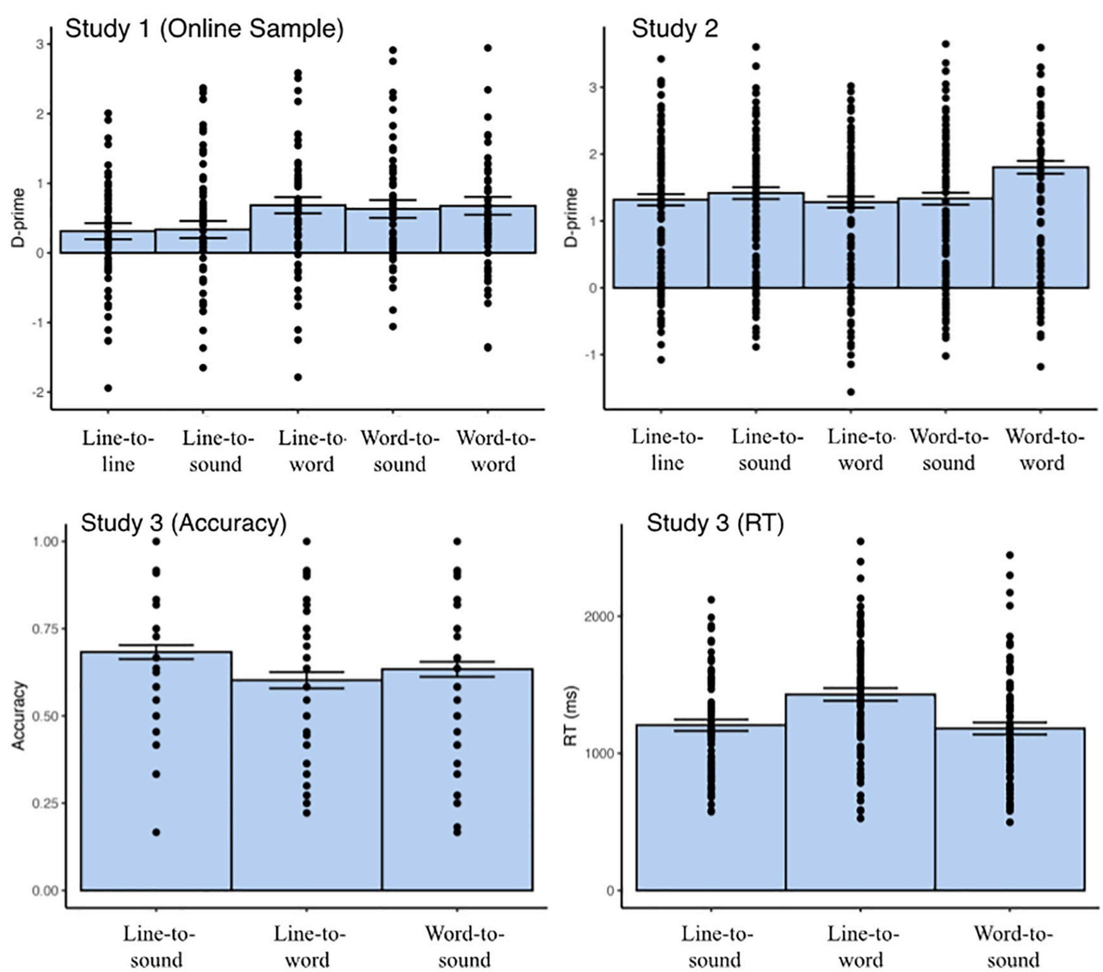

Fig. 2. Analogy task performance. Points represent individual participants' performance for each analogy trial (error bars indicate SE).

4. Study 2

4.1. Method

Study 2 sought to replicate cross-modality analogical mapping, and to further test the hypothesis that performance across analogy types was explained by a modality-general ability factor (i.e., “analo-*g*”). Additional Study 2 questions concerned whether analogical ability was associated with verbal and/or visuo-spatial abilities. A larger sample was recruited for Study 2 to achieve sufficient power to detect a one or two-factor solution with moderate-to-high communality between five planned observation variables (Mundfrom, Shaw, & Ke, 2005).

Participants ($N = 147$ following quality control exclusions based on outlying completion times, failed attention checks, and technical issues encountered during task administration; SI; $M_{age} = 29.41$; 60.5% female) completed all Study 1 trials online, excluding the above-described outlier trials, followed by the Vocabulary and Similarities sections of the Multidimensional Aptitude Battery-II (MAB_{verbal}), which measures verbal ability approximating Verbal IQ (Jackson, 1998), and Mental Rotation (MRT; Peters et al., 1995) to assess visuo-spatial ability.

4.2. Results

Accuracy was again high for both within-modality and, critically, cross-modality trial types (all $M > 73.3\%$, 95% CI [71.0%–83.8%]) and significantly above chance for both percent correct and d-prime (all $p < 0.0001_{Bonferroni\text{-}corrected}$, $d > 1.22$; Fig. 2), replicating cross-modality mapping of second-order analogical relations. Performance was similar for within and cross-modal analogies, again demonstrating that cross-modal analogies are not necessarily more challenging than analogies within a single modality.

To test the hypothesis of a modality-general analogical ability factor underlying performance across analogy types, exploratory factor analysis (SI) was conducted using maximum likelihood estimation for performance (d-prime) on all five analogy types. Consistent with the presence of a single underlying factor, this analysis indicated a first-to-second eigenvalue ratio exceeding 2.5 (Factor 1 = 3.27, Factor 2 = 0.30; Kaiser-Meyer-Olkin MSA = 0.88). Confirmatory factor analysis further supported a single factor (RMSEA = 0.05; CFI = 0.996).

Investigating the relationship of analogical reasoning to verbal and visuo-spatial abilities, performance for each analogy type was strongly associated with MAB_{verbal} (all $r > 0.45$, $p < 0.0001_{Bonferroni\text{-}corrected}$) and, more modestly, with MRT (all $r > 0.30$, $p < 0.01_{Bonferroni\text{-}corrected}$). Multiple linear regression to determine the independent contributions of MAB_{verbal} and MRT to analo-*g* (estimated for each participant as a scoring coefficient via least squares regression; SI) indicated that verbal ability (MAB_{verbal}; $\beta = 0.61$, 95% CI [0.45–0.70], $p < 0.001$) and visuo-spatial ability (MRT; $\beta = 0.16$, 95% CI [0.03–0.28], $p = 0.02$) were each independently predictive. Comparison of the effect sizes in this regression model via a seemingly unrelated estimate (suest) test indicated that MAB-based verbal IQ was a significantly stronger predictor of analo-*g* than MRT-based visuo-spatial ability ($\chi^2 = 19.34$, $p < 0.0001$). We next tested whether performance on the five different analogy types was intercorrelated when controlling for MRT and MAB_{verbal}, and found that it was (all partial $r > 0.36$, $p < 0.001$). Thus, individual differences in analogical ability were consistent across analogy types–ostensibly reflecting analo-*g*–and the presently measured verbal and visuo-spatial abilities did not fully account for these differences. Consistent with this interpretation, including MRT and MAB_{verbal} as additional observation variables in an exploratory factor analysis (along with d-prime scores for all five analogy types) yielded a less parsimonious model (BIC = 67.90) than analogy d-prime scores alone (BIC = 31.80). Given evidence that MAB was a stronger predictor of analo-*g* than was MRT, and prior evidence indicating that language learning supports analogy (Gentner, 2010), we conducted another exploratory factor analysis with all five analogy types and MAB alone. Fit for this model was again less parsimonious (BIC = 59.07) than analogy d-prime scores alone. Together, these results suggest that analo-*g* is better interpreted as reflecting analogical ability than as reflecting individual differences in verbal or visuo-spatial ability. Analo-*g* thus appears related to the forms of verbal and visuo-spatial ability measured here–especially verbal ability–but also distinct from those abilities.

Finally, we explored the contributions of MAB_{verbal} and MRT to performance on each analogy type via a series of multiple linear regressions. For all five analogy types, MAB_{verbal} remained significantly associated with performance (d-prime) when controlling for MRT (all $\beta > 0.38$, 95% CI [0.23–0.75], $p < 0.001$), whereas MRT predicted only lines-to-words ($\beta = 0.14$, 95% CI [0.002–0.27], $p = 0.047$) and words-to-words ($\beta = 0.16$, 95% CI [0.03–0.29], $p = 0.015$) when controlling for MAB_{verbal}. These results–and the above analo-*g* associations–implicate verbal ability as a modality-general correlate of analogical mapping, including fully non-verbal analogy types (lines-to-lines, and lines-to-sounds).

5. Study 3

5.1. Method

Study 3 further replicated and extended key results, focusing only on cross-modality analogy types. To avoid potential ceiling effects related to high accuracy on a large number of individual items (as observed in Studies 1 and 2), Study 3 included only a subset of the most challenging cross-modality (words-to-sounds; lines-to-words; lines-to-sounds) items (SI). We also investigated speed-of-responding (response time; RT) across analogy types. Additionally, to investigate relationships of analogy to fluid intelligence (Holyoak, 2012; Snow et al., 1984), all Study 3 participants ($N = 84$ following quality control; SI; $M_{age} = 28.58$ years; 55.95% male) performed an abbreviated Raven's Progressive Matrices (RPM; Raven & Raven, 1998). Sample size was sufficient to detect a one-factor model (which was anticipated in Study 3 based on the Study 2 results) for three planned observation variables with moderate-to-high levels of communality (Mundfrom et al., 2005).

For Study 3, the primary performance outcome was accuracy, rather than d-prime, because the selection of only higher-difficulty stimuli successfully yielded greater dynamic range in performance (i.e., no ceiling effects). Further, the smaller number of trials (12 stimuli per analogy type; 6 True and 6 False trials for each type), increased the likelihood of 100% hit rates and/or 0% false alarm rates on at least one analogy type, which confounds d-prime calculations (Macmillan & Creelman, 2004).

5.2. Results

Participants again showed significantly above-chance accuracy for all cross-modality analogy types (all $M > 59.9\%$, 95% CI [0.56–0.72], all $p < 0.0001_{Bonferroni\text{-}corrected}$, $d > 0.47$; Fig. 2). Replicating analo-*g*, exploratory factor analysis for accuracy (SI) indicated a single eigenvalue of 1.45 (Kaiser-Meyer-Olkin MSA = 0.68), with subsequent confirmatory factor analysis demonstrating acceptable fit (RMSEA<0.001; CFI > 0.99). A single factor also emerged for RT (Eigenvalue = 1.62; Kaiser-Meyer-Olkin MSA = 0.69; RMSEA<0.001; CFI > 0.99).

Investigating relationships to fluid intelligence, RPM performance was correlated with accuracy for all three analogy types (all $r > 0.39$, $p < 0.01_{Bonferroni\text{-}corrected}$), but not with RT (all $p > 0.13_{Bonferroni\text{-}corrected}$). RPM was also correlated with accuracy-based analo-*g* ($r = 0.50$, $p < 0.0001_{Bonferroni\text{-}corrected}$)–suggesting analo-*g* is related to fluid intelligence–but not with RT-based analo-*g* ($p = 0.13_{Bonferroni\text{-}corrected}$). Despite these associations, task performance (both accuracy and RT) was significantly intercorrelated across all analogy types after controlling for RPM (all partial $r > 0.34$, $p < 0.002$). Thus, individual differences in analogical ability were again consistent across analogy types–ostensibly reflecting analo-*g*–and RPM-based fluid intelligence did not fully account for these differences. Including RPM as an additional observation variable in an exploratory factor analysis (along with accuracies for all three analogy types) yielded a less parsimonious model (BIC = 308.20) than analogy accuracies alone (BIC = -119.86). Paralleling the Study 2 findings, this suggests that the factor is better interpreted as reflecting analogical ability than as reflecting individual differences in RPM. Thus, while RPM-based fluid intelligence was related to performance within and across analogy types, modality-general analogical ability (analo-*g*) appears distinguishable from RPM.

6. Discussion

Results replicating across four independent samples demonstrated analogical mapping between information received via distinct sensory and information-processing streams. Whereas distance/abstractness in analogy has previously been conceptualized within modalities (e.g., as quantitative "semantic distance" between words; Gentner & Markman, 1997; Green, 2016; Green et al., 2010; Vendetti, Wu, & Holyoak, 2014; Weinberger et al., 2016) and cross-modal correspondence has been well-demonstrated (e.g., Adelman et al., 2018; Cooperrider & Goldin-Meadow, 2017; Crisinel & Spence, 2010; Dolscheid et al., 2013; Forceville & Urios-Aparisi, 2009; Imai & Kita, 2014; Marks, 1987; Spence, 2011, 2020; Stevens & Marks, 1965; Thompson & Estes, 2011), the present study makes several novel contributions. By employing the A:B::C:D form of analogy, this appears to be the first study to explicitly test second-order relations between information presented in different *sensory* modalities (auditory vs. visual). More broadly, testing explicit second-order relations across stimuli presented in qualitatively different *information-processing* modalities (e.g., words, sounds, lines) appears to be novel. Focusing on explicit second-order relations is valuable because it affords greater certainty that participants actually formulate cross-modal second-order relations, rather than referring to "one-shot" categorical associations that appear to underlie at least some metaphoric correspondences. In addition, relative to previous cross-modal research, the cross-modal stimulus set devised for this study represents novel diversity of both first-order and second-order relations and complexity of analogical relations. In many cases, the stimuli not only present an explicit second-order relation, but employ mappings based on quantitatively specified ratios (e.g., the differences in pitch between a series of rising and falling tones is quantitatively comparable to the differences in distance between a series of lines on the screen). This further reinforces the mapping of item-specific second-order relations, and appears to be novel for mappings across sensory modalities. Some research has investigated second-order relations based on quantitative ratios of space vs. time or amount (Gattis, 2002, 2004) but, as noted above, it is not clear that such work crosses boundaries of modality (e.g., participants compared two visually presented line graphs to make inferences about their relative slopes).

Performance on all analogy types was explained by a single factor, indicating the presence of a modality-general analogical ability (analo-*g*). Analo-*g* was strongly related to fluid intelligence measured via Raven's Progressive Matrices, but RPM did not fully account for the intercorrelations between performance on cross-modal analogy types, and the inclusion of RPM yielded a less parsimonious factor structure than analogy performance alone. Prior work suggests RPM is a form of spatial analogical reasoning (Lovett, Forbus, & Usher, 2010), but the present findings suggest an analogical ability that may not be fully captured by RPM. This may be because, whereas RPM is a visuo-spatial reasoning task, multiple accounts of analogical reasoning–and relational reasoning more broadly–emphasize the contribution of verbal/semantic processes (Braine & O'Brien, 1998; Gelman et al., 2009; Gentner & Forbus, 2011; Gentner & Markman, 2006; Holyoak & Thagard, 1989; Hummel & Holyoak, 1997; Rips, 1994). A strategy that might have supported at least some of the cross-modality analogical mapping observed here is verbalization of relations presented in distinct modalities–including nonverbal modalities–to facilitate subsequent mapping of the verbal/semantic representations. Notably, RPM involves analogical relations (Holyoak, 2012; Lovett et al., 2010), but these relations are often complex and may thus be difficult to verbalize. This might distinguish RPM from other forms of analogy. Future research should investigate whether the verbalizability of analogical relations influences cross-modality analogical mapping and association with analo-*g*. Given prior work demonstrating that linguistic cues facilitate cross-modal mapping in young children (Starr & Srinivasan, 2018), it appears likely that verbalization of relations may play a similar role in analogical reasoning. The present finding that analo-*g* showed significantly stronger association with verbal ability than visuo-spatial ability, and that verbal ability predicted performance within each analogy type after accounting for visuo-spatial ability–including fully nonverbal analogies–appears consistent with accounts of analogy that include verbal/semantic representation. However, many of these accounts also posit spatialized (e.g., array) information structures functioning in concert with verbal/semantic representations (e.g., Gentner & Forbus, 2011; Hummel & Holyoak, 2003), which broadly coheres with the finding that visuo-spatial ability – in addition to verbal ability – was independently predictive of analo-g. The use of single measures to represent the broad constructs of verbal and spatial ability is a limitation of the present study – this was motivated by an effort not to overtax participants' attention in a lengthy and complex paradigm – and additional work is necessary to more fully characterize the influences of verbal and spatial abilities (Uttal, Miller, & Newcombe, 2013).

Given that experiences involving multiple sensory and informational modalities are the rule rather than the exception in real-world contexts, the present evidence suggests novel research questions about the capacity of second-order analogical relations to support environmental learning and creativity, and points to potential cross-modal expansions of extant applications of analogy in AI (Roads & Love, 2020), and to support education and innovation (Moreno et al., 2014; Vendetti et al., 2014; Vendetti, Matlen, Richland, & Bunge, 2015). Future research on these questions should seek to extend approaches for identifying cross-modal second-order relations into naturalistic/real-world contexts.

Author contributions

Adam B. Weinberger.: Conceptualization, Methodology, Formal analysis, Investigation, Writing – Original draft, Writing – Review & editing, Visualization, Project administration. Natalie M. Gallagher: Conceptualization, Methodology, Formal analysis, Investigation, Writing – Review & editing, Project administration. Griffin Colaizzi: Methodology, Investigation. Nathaniel Liu: Methodology, Investigation. Natalie Parrott: Methodology, Investigation. Edward Fearon: Methodology, Investigation. Neelam Shaikh: Writing – Original draft. Adam E. Green: Conceptualization, Writing – Review & editing, Supervision, Project administration, Funding acquisition.

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Author note

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Declaration of Competing Interest

The authors declare no competing interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2022.105029.

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