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Modality-specific dynamics and context dependent involvement of visuospatial and verbal abilities in analogical mapping

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Abstract

This work examines the influence of sensory modality constraints on analogical reasoning, focusing on the sensory modality in which the analogy is presented, the influence of verbal abilities, visuospatial abilities and structural factors like verbalisability and visualisability on analogical performance. Through three experiments, we explored how presentation modalities (written, auditory, and mixed) affect the accuracy and latency of analogical reasoning tasks in an A:B::C:D format. Results showed that written presentations yielded the highest accuracy and fastest response times, followed by auditory and mixed conditions. Verbal abilities, assessed with a naming task, strongly predicted performance across all modalities, while visuospatial abilities, measured with a mental rotation task, were particularly relevant in the mixed condition. Higher verbalisability and visualisability difficulty reduced performance across all conditions but to different extents depending on the modality of presentation, reflecting flexible engagement of each of these abilities depending on the task demands. These findings underscore modality-specific dynamics in analogical reasoning and highlight the critical role of cognitive abilities and the structural factors that are verbalisability and visualisability of the relational structure in shaping the ability to solve analogies.

Keywords: Analogy;modality;visualisability;verbalisability

Introduction

The importance of studying analogical reasoning

Analogical reasoning is a cognitive process in which information or meaning is transferred from a known domain (the source) to an unfamiliar or abstract domain (the target). This transfer relies on recognizing a shared relational structure between the two domains rather than superficial similarities more often than not. A classic example is the water–circuit analogy, in which relations among pressure, flow, and resistance in hydraulics are mapped onto voltage, current, and electrical resistance. Analogical ability encompasses the ability to recognize such relational similarities across different contexts and domains. It is a fundamental aspect of human cognition and plays a crucial role in learning, problem solving, and creativity.

The stages of analogical reasoning

Analogical reasoning is commonly described as a sequence of five core stages (Holyoak, 2012). First, *retrieval* involves identifying a relevant source analog from memory based on perceived similarity to the target problem. Second, *mapping* consists in establishing structured correspondences between elements and relations in the source and target domains. Third, *inference* allows novel information about the target to be generated from the mapped relations. Fourth, *evaluation* assesses the validity and relevance of the inferred knowledge. Finally, *schema induction* abstracts common relational structures from specific analogies, supporting generalization to future problems (Gentner, 1983). Our study primarily focuses on the mapping stage as it is the core process that is at the heart of the modality generality or specificity debate, and therefore, a particular emphasis is put on the question of whether analogical mapping operates in a modality-general or modality-specific manner.

Mapping: modality-general or modality-specific?

To address this question, it is useful to distinguish between *sensory modality* and *informational modality*. Sensory modality refers to the perceptual channel through which information is delivered (e.g., visual or auditory), whereas informational modality refers to the representational format in which the content is processed (e.g., verbal or visuospatial). Written and spoken words for example differ in sensory modality but share the same informational modality.

According to an informational *modality-general* view, analogical mapping relies on abstract, amodal representations of relational structure. Under this account, initial encoding may occur in a specific sensory modality, but mapping operates on representations that are independent of presentation format. Consequently, once differences in sensory encoding latencies are accounted for, performance should not differ across modalities.

In contrast, informational *modality-specific* models propose that analogical mapping is at least partially constrained by the representational format in which information is encoded. Differences in sensory or informational modality may affect the ease with which relational correspondences are established, particularly in cross-modal or mixed-format analogies.

Sensory modality effects on verbal analogy performance

Little disagreement exists over the role that differences in sensory encoding latencies across modalities play in influencing processing time and accuracy. Written presentation affords persistent access to information, which reduces transient working-memory demands and facilitates more deliberative processing. In contrast, auditory presentation is sequential and must be actively maintained, increasing working-memory load despite faster initial encoding latencies (Ginns, 2005; Geipel & Keysar, 2022).

If analogical mapping operates through truly modality-general mechanisms, performance differences between written and auditory verbal analogies should be entirely attributable to sensory encoding constraints. Conversely, if dif-

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ferences persist after accounting for sensory encoding latencies, this would support modality-specific processing during the mapping stage.

Verbalizability and visualisability

Prior work indicates that both verbal and visuospatial abilities contribute to analogical reasoning, even when the analogs are not explicitly verbal or spatial. For example, providing relational labels improves children's performance on visuospatial match-to-sample tasks (Gentner & Smith, 2012), and children with language impairments perform worse on nonverbal analogy tasks than age-matched peers (Krzemien et al., 2017). Visuospatial abilities also predict performance on abstract analogies, and spatial training can enhance analogical reasoning (Corral & Burte, 2025). Visual re-representation may support purely symbolic analogies by making relational structure more concrete (Navarrete-Ulloa & Trench, 2025).

These findings suggest that verbal and visuospatial abilities indeed do support analogical mapping but little is known about the ”how” of this contribution. The most intuitive possibility is that verbal abilities may facilitate the identification and maintenance of relational information in working memory, particularly for abstract relations, whereas visuospatial abilities may support mapping by enabling mental representation and manipulation of relational structure. Furthermore, Weinberger et al. (2022) showed that both verbal and visuospatial abilities contribute to analogical reasoning in a modality-invariant manner, with verbal ability contributing more strongly overall. Building on this work, we examine whether the contribution of these abilities is further shaped by structural properties of the relations themselves, specifically, their verbalisability and visualisability, and whether these effects depend on the modality in which analogies are presented (written, auditory, or mixed).

Experiments 1 and 2 (Norming studies)

Twenty six participants with comparable higher education levels, French as their first language, and no verbal or visuospatial impairments, participated in this study.

Verbalisability Measure

Participants were presented with pairs of stimuli followed by a second pair portraying the same relationship. Participants described the relationship using one or two words and rated the difficulty of verbalizing the relationships on a scale from 1 (very easy) to 5 (very difficult).

Visualisability measure

From the responses given in the verbalisability measure, we have extracted the most recurring relationship for each analogy. Participants described how they represented these relationships visually and rated the difficulty they encountered in visualizing them using a scale from 1 (very easy) to 5 (very difficult).

Both response times as well as difficulty ratings were collected and used to create verbalisability difficulty and visualisability difficulty scores. Weighting difficulty scores by response times (RTs) ensures that more cognitively demanding items have a greater influence, normalizes individual differences in processing speed, and enhances the sensitivity of difficulty ratings by distinguishing between perceived and actual cognitive effort.

Experiment 3 (Main study)

Participants

A total of 65 French speaking participants with no history of neurological or linguistic disorders were recruited (aged 18 to 32).

Procedure

Each participant completes two tasks on top of the main analogical reasoning task: a 3D mental rotation task (MR task), which serves as visuospatial abilities proxy, and an object naming task(Naming task), which serves as a verbal abilities proxy. The sequence of these tasks were controlled using a Latin square design to minimize order effects and ensure balanced exposure to task variations.

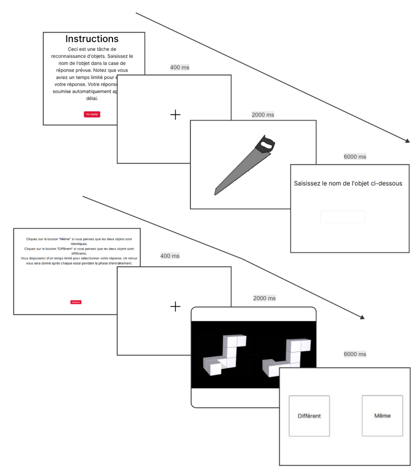

Figure 1: Illustration of naming (top) and mental rotation (bottom) tasks

The analogical reasoning tasks were presented in an A:B::C:? format, designed to emphasize relational reasoning over surface similarities. In this task, participants were shown a pair of stimuli (A:B) followed by a single stimulus (C) and must choose the appropriate match (D) from four response options. To ensure participants engage in true relational mapping, the distractors were intentionally designed to share either surface similarity or semantic similarity or phonemic similarity with the c element of the analogy. This control differentiates analogical reasoning from simpler processes like surface-based matching and metaphorical associations.

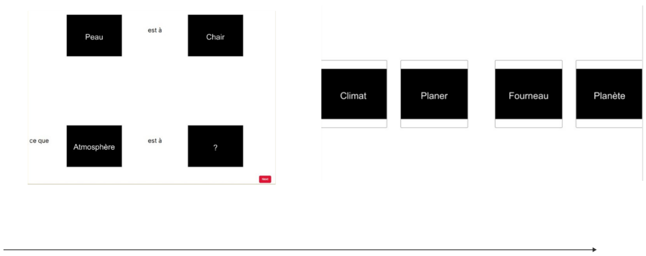

Figure 2: Illustration of the written condition in the analogy task following the instruction screen :textual stimuli

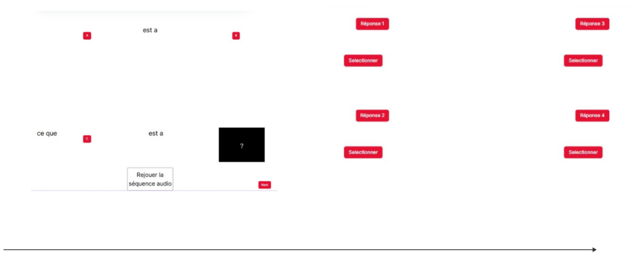

Figure 3: Illustration of the audio condition in the analogy task following the instruction screen : spoken stimuli

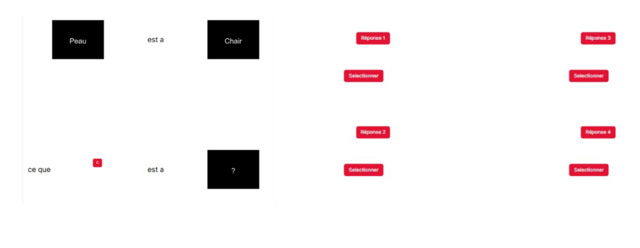

Figure 4: Illustration of the mixed condition in the analogy task following the instruction screen : a combination of written and audio words.

Data processing and analysis

Corrected response time calculation : In an attempt to isolate modality specific sensory encoding from downstream cognitive operations, we corrected raw response times by subtracting empirically derived sensory latencies and individually fit mechanical operation times. Hierarchical models of language processing posit that visual and auditory inputs undergo distinct early encoding stages before common lexical and semantic processes ensue (Friederici, 2011). If these modality-specific latencies and mechanical time latencies are not accounted for, observed differences in decision time may reflect sensory encoding or mechanical task demands only, rather than higher order cognitive processing disparities, including the mapping process.

Estimation of sensory encoding time for written vs spoken words : Visual word recognition has been characterized in multiple studies as completing its orthographic encoding before 200 ms. In their review, Carreiras et al. (2014) synthesize electrophysiological and MEG (Magnetoencephalography) findings to show that pre-lexical orthographic processes, including letter-string and word-form mapping in the visual word form area, are reliably concluded by approximately 150–200 ms post-stimulus. This timing is further supported by EEG studies demonstrating that the N170 component, which indexes orthographic analysis, peaks between 160–180 ms and is insensitive to lexical variables (Maurer et al., 2005). Consequently, we adopt a conservative midpoint of 165 ms to represent visual sensory encoding latency. Auditory word recognition unfolds over a longer temporal window due to the sequential nature of speech. Oscillatory entrainment and MEG evidence show that phoneme level processing initially occurs within the first 100 ms, but the integration of successive phonemic segments into a stable lexical representation stretches out to around 250 ms post-onset (Giraud & Poeppel, 2012). This theoretical framework is supported by studies of continuous speech by Gross et al. (2013) that show that cortical oscillations synchronize with syllabic and phonemic rates such that fully resolved word forms emerge around 220–280 ms. Accordingly, we set the auditory sensory encoding latency at 250 ms, reflecting the point at which phoneme integration yields a recognizable word form. We do recognize that these estimations are based on averages that might not generalize across participants and that individual differences in reading fluency or phonological processing may introduce residual variability in the corrected latencies. The corrections should be understood as theoretically motivated approximations that attempt to reduce systematic modality-level confounds rather than eliminate sensory encoding variance entirely.

Method for estimating mechanical click time : Due to the lack of direct measurement of individual screen search and click latencies, we estimated these latencies by extracting the difference between the offset of the last audio on the presentation screen and the button click to move to the response screen. Considering that some participants took a long time to click the button to move to the response screen after the last audio's offset, we used only the first quantile (Q1) of each participant's response times for clicks and replaced values outside this range with the average of these latencies.

By subtracting these modality-specific estimated latencies (165 ms for written words and 250 ms for spoken words, multiplied by the number of words a participant heard or saw) and the mechanical time difference (informed by the number of clicks associated with auditory stimulus play) from each participant's raw reaction time. These corrections are an attempt at ensuring that subsequent comparisons of modality-specific performance reflect post-sensory cognitive dynamics, rather than sensory encoding or mechanical demand differences.

Results and discussion

Correlation between weighted verbalisability and visualisability difficulty scores

A Spearman correlation was conducted to examine the relationship between weighted verbalisability and weighted visualisability difficulty scores. The analysis revealed a moderate positive correlation, $\rho = .35$, $p < .001$, indicating that analogy relationships that are harder to verbalize also tend to be harder to visualize. However, the correlation is not sufficiently strong to suggest redundancy between the two measures. This supports the interpretation that they capture related but distinct dimensions of semantic difficulty, justifying their separate inclusion as predictors in the subsequent modeling of analogy performance.

Modality effects on performance

Accuracy : Descriptive statistics revealed that the Written condition achieved the highest mean accuracy ($M = 0.82$, $SE = 0.02$), followed by the Mixed ($M = 0.77$, $SE = 0.02$) and Audio ($M = 0.76$, $SE = 0.02$) conditions. Given the within-subject design, normality was assessed in each condition using the Shapiro–Wilk test. The results indicated significant deviations from normality in all three conditions (all $p < .001$). A Friedman test was therefore conducted to evaluate differences in analogy performance across the three conditions. This test revealed a statistically significant difference, $\chi^2(2) = 7.18$, $p = .028$, suggesting that analogy modality had a reliable effect on performance. Post hoc pairwise comparisons using Wilcoxon signed-rank tests indicated that performance in the Written condition was significantly higher than in the Audio condition ($W = 377.0$, $p = .004$) and also significantly higher than in the Mixed condition ($W = 464.5$, $p = .024$). In contrast, no significant difference was found between the Mixed and Audio conditions ($W = 736.0$, $p = .773$).

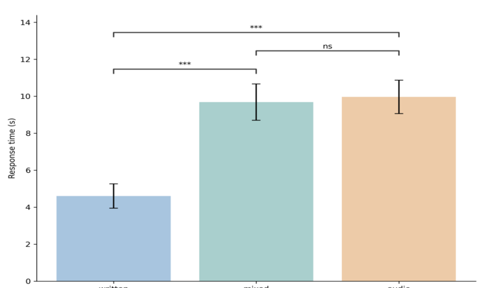

Figure 5: Performance by analogy modality condition

This pattern suggests that verbal analogical reasoning is facilitated when words are read as compared to when they are heard, consistent with literature suggesting better resolution ability of written problems as compared to spoken ones (Geipel & Keysar, 2022).

Response time : Due to violations of normality in corrected reaction times across all three conditions (Shapiro–Wilk test, all $p < .001$), a non-parametric Friedman test was conducted. The test revealed a significant effect of condition on reaction times, $\chi^2(2) = 55.35$, $p < .001$. Follow-up Wilcoxon signed-rank tests with Bonferroni correction showed that participants responded significantly faster in the Written condition compared to both the Mixed condition ($W = 22.0$, $p_{\text{corr}} < .001$) and the Audio condition ($W = 54.0$, $p_{\text{corr}} < .001$). Additionally, responses were significantly faster in the Audio condition than in the Mixed condition ($W = 173.0$, $p_{\text{corr}} < .001$).

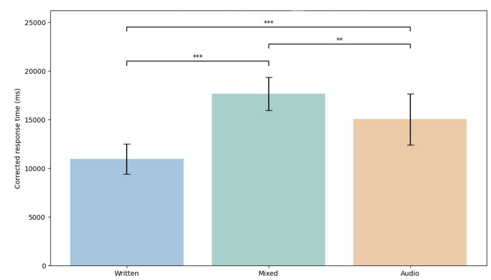

Figure 6: Corrected response time by condition

The longer latencies in the Audio and Mixed conditions indicate a higher cognitive load likely associated with working memory and mapping demands.

Overall, these results align with prior research suggesting that speech-based inputs involve transient and sequential information processing, which can hinder relational mapping when compared to simultaneous visual presentation. Interestingly, the Mixed condition yielded the slowest response times, even compared to the Audio condition, despite similar accuracy rates. This may suggest a modality-switch cost or interference effect, wherein integrating information across modalities requires additional cognitive resources, potentially disrupting mapping processes. These results challenge the assertion that performance is comparable across and within modalities (Weinberger et al., 2022), instead aligning with modality-specific models that emphasize distinct processing demands across sensory channels.

Individual differences in verbal and visuospatial abilities

Spearman correlation analyses revealed that verbal abilities, measured by naming scores, consistently predicted analogy performance across all modalities (Written: $\rho = .435$, $p = .0003$; Mixed: $\rho = .377$, $p = .0018$; Audio: $\rho = .313$, $p = .0106$). This strong correlation, particularly in the Written condition, aligns with expectations for a verbal analogical reasoning task, where verbal encoding facilitates performance. In contrast, visuospatial abilities, measured by mental rotation scores, significantly predicted performance only in the Mixed condition ($\rho = .309$, $p = .0115$), but not in the Written ($\rho = .222$, $p = .0736$) or Audio ($\rho = .063$, $p = .6166$) conditions. Compared to modality effects, where Written presentation yielded superior performance, these results suggest that verbal abilities dominate across conditions, while visuospatial abilities are selectively engaged in the Mixed condition, likely due to modality-switch demands.

Predictivity of structural factors:verbalisability and visualisability

Accuracy : To examine how these difficulty dimensions influenced performance, a Generalized Linear Mixed Model (GLMM) with random intercepts for participants was fitted to predict analogy accuracy. The initial model included centered weighted verbalisability and visualisability scores as fixed effects. Both predictors significantly affected performance. Higher verbalisability difficulty was associated with a lower probability of a correct response ($\beta = -1.44$, $p < .001$), suggesting that analogies involving relationships that were harder to verbalize were less likely to be solved correctly. Similarly, greater visualisability difficulty predicted reduced accuracy ($\beta = -0.22$, $p = .017$), indicating that difficulty in mentally visualizing the relation also impaired performance.

To assess whether the effect of these difficulty dimensions varied across modality conditions, we fitted a second model including fixed effects for condition (with Audio as the reference level) and interaction terms between condition and both difficulty measures (see Table 1). Model comparison via a likelihood ratio test revealed that including these interaction terms significantly improved model fit relative to the simpler model without condition terms ($\chi^2(6) = 12.82$, $p = .046$).

Table 1: Generalized linear mixed model predicting analogy accuracy with centered difficulty × condition interactions (Verb.=Verbalisability; Visu.=Visualisability; Diff.=Difficulty)

Predictor	Estimate (β)	SE	z	p
Intercept	1.33	0.14	9.28	<001***
Verb. Diff.	-1.44	0.34	-4.21	<001***
Visu. Diff	-0.22	0.09	-2.39	0.017*
Mixed	0.10	0.16	0.63	0.528
Written	0.57	0.17	3.26	0.001**
Verb. × Mixed	-0.15	0.50	-0.30	0.763
Verb. × Written	-0.96	0.53	-1.81	0.070
Visu. × Mixed	0.02	0.14	0.15	0.880
Visu. × Written	0.01	0.14	0.04	0.965

Inspection of the interaction terms revealed notable effects in the Written condition. The interaction between verbalisability difficulty and the Written condition approached significance ($\beta = -0.96$, $p = .070$), suggesting a trend toward a stronger negative effect in this modality. This implies that in the Written condition, performance was likely sensitive to how difficult it was to verbalize the relationship. When combining the main and interaction terms, the total effect of verbalisability difficulty in the Written condition was approximately $\beta = -2.40$ supporting the interpretation that verbalisability difficulty exerted a substantially larger negative effect on accuracy in the Written condition. In contrast, the interaction between visualisability difficulty and the Written condition was not significant ($\beta = 0.01$, $p = .965$), indicating that the negative effect of visualisability difficulty ($\beta = -0.22$) was stable across conditions. Similarly, neither interaction term involving the Mixed condition reached significance ($\beta = -0.15$, $p = .763$ for verbalisability; $\beta = 0.02$, $p = .880$ for visualisability), suggesting that this condition did not modulate participants' reliance on either difficulty dimension.

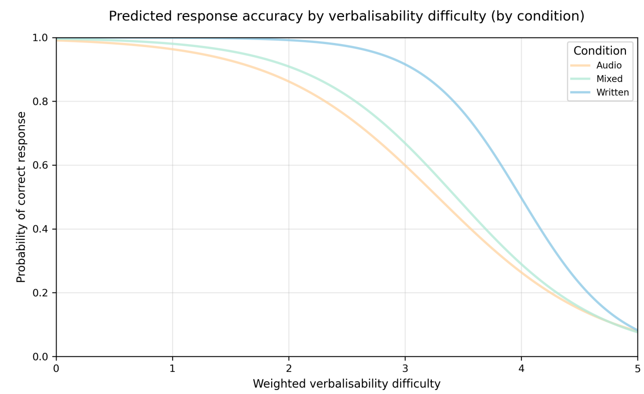

Figure 7: Predicted probability of correct analogy response as a function of weighted verbalisability difficulty, shown by presentation modality.

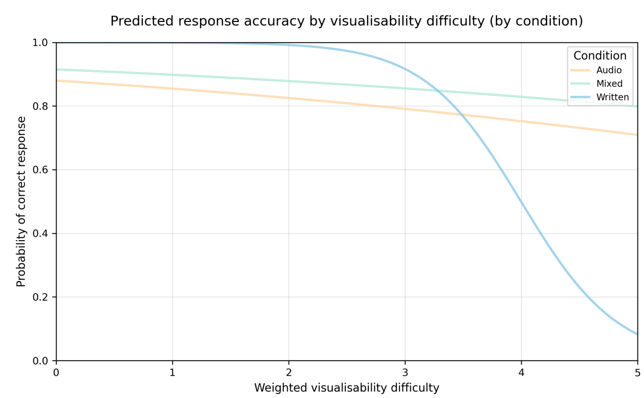

Figure 8: Predicted probability of correct analogy response as a function of weighted visualisability difficulty, shown by presentation modality.

Response time : Another Generalized Linear Mixed Model (GLMM) with random intercepts for participants was fitted to predict corrected response times. The initial model included weighted verbalisability and visualisability scores as fixed effects, along with condition as a factor (with Audio as the reference level). This main effects model revealed that verbalisability difficulty significantly affected response times ($\beta = 3723.86$, $p = .018$), with higher difficulty associated with longer response times. Visualisability difficulty, however, did not significantly predict response times ($\beta = -703.24$, $p = .136$). To assess whether the effect of these difficulty dimensions varied across modality conditions, a second model with interaction terms was fitted (see Table 2). A likelihood ratio test confirmed significantly better model fit compared to the main effects model ($\chi^2(4) = 96.02$, $p < .001$).

Table 2: Generalized linear mixed model predicting response times with centered difficulty × condition interactions (Verb.=Verbalisability; Visu.=Visualisability; Diff.=Difficulty)

Predictor	**Estimate (β)**	**SE**	***z***	***p***
Intercept	22816.45	6269.88	3.64	<001***
Verb. Diff.	-1494.28	2832.50	-0.53	0.598
Visu. Diff.	-2020.18	819.06	-2.47	0.014*
Mixed	-11963.86	8890.33	-1.35	0.178
Written	-41159.32	8898.85	-4.63	<001***
Verb. × Mixed	351.35	4086.13	0.09	0.931
Verb. × Written	15439.72	4088.87	3.78	<001***
Visu. × Mixed	2774.01	1176.30	2.36	0.018*
Visu. × Written	1246.98	1183.63	1.05	0.292

Inspection of the interaction terms revealed significant modality-specific effects. Most notably, the interaction between verbalisability difficulty and the Written condition was highly significant ($\beta = 15439.72$, $p < .001$), indicating a strong positive effect in this modality on response times. When combining main and interaction effects, the total effect of verbalisability difficulty in the Written condition was $\beta = 13945.44$, suggesting that analogies with harder-to-verbalize relationships required substantially more time to process when presented as text. In contrast, the effect of verbalisability on RT was non-significant in the Audio condition ($\beta = -1494.28$, $p = .598$). The interaction between verbalisability and Mixed condition was not significant $\beta = 351.35$, $p = .931$). For visualisability, there was a significant negative effect in the Audio condition ($\beta = 2020.18$, $p = .014$), indicating faster responses for harder to visualise relationships when analogies were presented auditorily. The interaction with the Mixed condition reversed this effect ($\beta = 2774.01, p = .018$), yielding a positive combined effect ($\beta = 753.82$). The interaction with the Written condition was not significant ($\beta = 1246.98, p = .292$). These response time results suggest that text presentation in particular appears to tax analogy performance when relationships are difficult to verbalize, possibly due to the reliance on sequential verbal rehearsal. This finding aligns with our interpretation that the interaction between verbalisability and the Written condition observed in our accuracy measure reflects heightened sensitivity to verbalisability difficulty in written presentation. In contrast, verbalisability effects on response times were negligible in the Audio and Mixed conditions, indicative of a possible shift in strategies when elements of the analogy are presented in audio form. Furthermore, the observation of faster

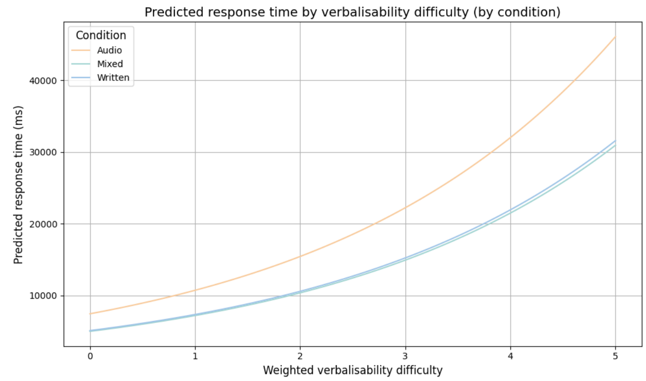

Figure 9: Predicted response times as a function of weighted verbalisability difficulty, shown by presentation modality

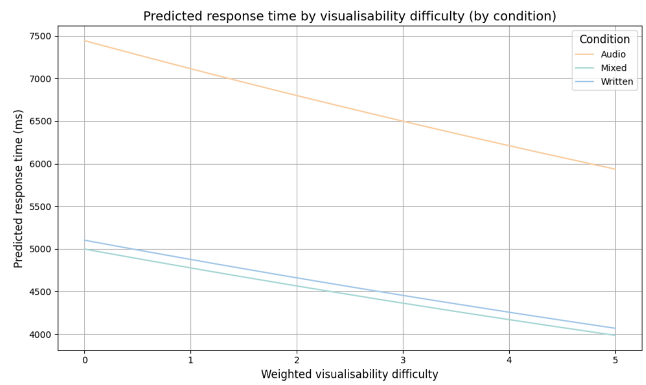

Figure 10: Predicted response times as a function of weighted visualisability difficulty, shown by presentation modality.

responses for harder-to-visualize relationships in the Audio condition was rather surprising to us. One possible interpretation is that this pattern might reflect abandonment of visualization attempts when relationships resist spatial representation. It is important to bear in mind that these interpretations are not directly supported by the current data and that they should be subject to more straightforward testing in the future.

Taken together, these findings diverge from previous results (Weinberger et al., 2022), which reported equal contributions of verbal and visual abilities across modalities, and support modality-specific models instead.

Conclusion

Overall, these results highlight the cognitive system's remarkable flexibility in adapting to sensory input constraints. They suggest that analogical reasoning instruction should consider presentation modality effects, individual verbal and visuospatial abilities differences, as well as how easy it is to verbalize and visually represent the relational structure of the analogs.

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