Aging of Problem-Solving Analogical Reasoning: The Role of Surface and Structural Similarity Postprint

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Abstract

A 2 (age: older/younger) × 2 (surface similarity: high/low) × 2 (structural similarity: high/low) three-factor mixed design was employed to examine the role of surface and structural information in analogical reasoning aging within a problem-solving paradigm. The results indicated that older adults' analogical reasoning performance was significantly worse than that of younger adults. Enhanced surface and structural similarity between source and target problems facilitated retrieval of source problems and improved reasoning quality. Surface similarity was more critical for older adults, whereas structural similarity was more critical for younger adults.

Full Text

The Role of Surface and Structural Similarity in Aging of Problem-Solving Based Analogical Reasoning

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Abstract

This study employed a 2 (age: older/younger) × 2 (surface similarity: high/low) × 2 (structural similarity: high/low) mixed factorial design to investigate the roles of surface and structural information in analogical reasoning aging based on the problem-solving paradigm. Results revealed that older adults performed significantly worse than younger adults in analogical reasoning. Increased surface and structural similarity between source and target problems facilitated source retrieval and improved reasoning quality. For older adults, surface similarity was more important, whereas for younger adults, structural similarity played a more critical role.

Keywords: analogical reasoning; transfer; problem-solving paradigm; surface similarity; structural similarity
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Analogical reasoning refers to the transfer of knowledge about problem-solving methods from one situation or domain (the source problem) to another situation or domain (the target problem) (Gentner, 1988). For example, Lu Ban invented the saw after being cut by a leaf with serrated edges, and humans manufactured airplanes based on the principles of bird flight. Analogy is an adaptive mechanism that can reduce uncertainty in problem-solving under natural conditions (Chan, Paletz, & Schunn, 2012), and both analogy and similarity play important roles in learning and transfer (Gentner, Rattermann, & Forbus, 1993).

Research on analogical reasoning has employed two main task paradigms. The first is the classical analogical reasoning task paradigm proposed by Piaget and later modified by Sternberg (Sternberg & Nigro, 1980), which typically takes the form a:b::c:d, such as bread:milk::youtiao:soymilk. That is, people can infer the relationship between youtiao and soymilk (a Chinese breakfast pairing) from the relationship between bread and milk (a Western breakfast pairing). The second is the problem-solving reasoning task (Chen & Siegler, 2013), where individuals facing a novel problem (target) utilize solutions from previously encountered similar situations (source) to solve the current problem. For instance, participants might read a source problem: "Old Li, a woodcutter, was pushing a cart of firewood down the mountain. Feeling thirsty, he took out his water flask to drink. Unexpectedly, the firewood cart caught fire, but there was no water source nearby. In desperation, Old Li quickly splashed the water from his flask onto the cart, but the fire remained fierce due to the insufficient water. He could only watch as his cart burned to ashes." In this scenario, the woodcutter' s solution was to splash available liquid (soup) on the burning cart, but it was a drop in the bucket and failed to extinguish the fire. Participants would then read a target problem: "Old Zhang, a farmer, had picked a cart of grass to take home for his livestock. Feeling hungry, he stopped to rest and took out a bowl of soup. Unexpectedly, the weather was so hot that Old Zhang discovered the grass was being scorched, emitting a pungent smell." Participants were asked what would happen next in this scenario. Based on the similar plot development in the source problem, the answer should be: "Old Zhang quickly splashed the soup in his hand onto the grass, but it was merely a drop in the bucket, and he could only watch as all the grass in his cart dried up."

Previous studies using word reasoning (Bugaiska & Thibaut, 2015; Clark, Gardner, Brown, & Howell, 1990), letter sequence inductive reasoning (Saczynski, Willis, & Schaie, 2002), and analogical sentence relations with known premises

(Salthouse, Legg, Palmon, & Mitchell, 1990) have found universal declines in analogical reasoning abilities among older adults. Older adults experience difficulties integrating relations during analogical reasoning and struggle to inhibit interference from irrelevant features on correct information (Viskontas, Holyoak, & Knowlton, 2005), along with slower reaction times (Clark et al., 1990). Regarding neural mechanisms, researchers have found correlations between white matter integrity and reasoning abilities in cognitive test batteries, as well as between white matter integrity and daily functioning in older adults. Frontal lobe white matter tracts and interhemispheric communication play important roles in higher-order cognitive functions (Monge, Greenwood, Parasuraman, & Strenziok, 2016). However, experimental materials in classical analogical reasoning tasks typically involve graphics, letters, and numbers—formats that may be unfamiliar to older adults and provide relatively limited background information. Problem-solving based reasoning tasks usually present tasks as stories or problems, requiring participants to complete target problems based on source problems from long-term memory. The parts to be completed do not involve the main storyline (HOR) but simulate ill-defined problems in real problem-solving situations. Compared to classical analogical reasoning tasks, problem-solving based reasoning tasks can provide more contextual information, which may help older adults complete reasoning tasks. Previous research has found that children perform better in problem-solving based analogical reasoning tasks than in classical tasks (Brown & Kane, 1988), and presenting more information through video also facilitates reasoning (Chen & Siegler, 2013). Therefore, we hypothesized that using this paradigm would be more helpful for older adults to complete reasoning tasks than classical analogical tasks. Additionally, older adults have more opportunities in daily life to encounter situations where they can apply previous problem-solving methods to new problems, and their own life experience and wisdom may also help them complete problem-solving reasoning tasks (Jeste & Oswald, 2014). However, current research on problem-solving based reasoning is limited, with participants mostly being children (Tunteler, 2002), adolescents (Jablansky, Alexander, Dumas, & Compton, 2016), and university students (Catrambone, 2002; Ross, 1989). Therefore, one question this study examined is whether older adults also show poor performance in problem-solving based analogical reasoning tasks.

In developmental research, understanding and representing relational similarity is an important internal foundation for the development of reasoning abilities (Gentner, 1988; Goswami, 1991; Xin, 2007), applicable to both classical reasoning tasks (a:b::c:d) and problem-solving tasks (Chen & Siegler, 2013). Similarity affects the representation of others' behaviors in social relationships (Liviatan, Trope, & Liberman, 2008), as well as judgment and decision-making biases (Koehler, Brenner, Liberman, & Tversky, 1996). Similarity between corresponding components of target and source problems can facilitate source problem retrieval (Catrambone, 2002; Holyoak & Koh, 1987). Since the 1990s, researchers (Catrambone, 2002; Gentner et al., 1993) have decomposed information in problem-solving analogical reasoning tasks into two types: surface information and structural information. Surface information includes entities and attributes. Entities typically refer to people and objects in stories, such as "woodcutter" and "firewood," while attributes describe properties of entities, such as "tall." Structural information includes first-order relations and higher-order relations. First-order relations express relationships between entities, generally verbs, such as "splash" and "catch fire" in stories. Higher-order relations are abstract rules extracted from the entire problem, such as "a drop in the bucket." Source and target problems must share a higher-order relation to form an analogy. Recognition of surface and structural similarity between source and target problems guides the retrieval and selection of relevant source problems for application to target problem solving.

Similarity between source and target problem components can facilitate source retrieval and improve reasoning performance (Catrambone, 2002; Holyoak & Koh, 1987), but the role of similarity is complex, and there has been ongoing debate about whether surface or structural similarity has greater impact (similar debate; Bulloch & Opfer, 2009). On one hand, some studies have found that accurate reasoning depends on structural similarity, such as causal structures (Holyoak & Koh, 1987) and principle application. Gentner (1983) argued that first-order and higher-order relations in problems play primary roles in problem solving, and whether problem solvers can induce this higher-order structural relationship is key to solving problems. Holyoak and Koh's (1987) schema theory posits that schemas—summaries of structural information—are generated during source problem encoding, allowing problem solving without directly recalling the source problem when the target problem appears. Structural similarity thus seems to more strongly activate source retrieval. Schnotz and Baadte (2015) manipulated surface and deep structures in graphic reasoning and found that when young adult participants recalled deep structures, their recall accuracy was better, with deep structures showing stronger effects than surface structures.

On the other hand, some research suggests that similarity-based prompting effects originate from surface similarity rather than structural similarity. Ross (1984) found that similarity in story causal relationships had strong effects on accessing target stories (i.e., retrieving analogical sources) but little effect on accurately applying the story' s rules (i.e., structural information). Research with children also found that correct mapping depended more on surface similarity (Pierce & Gholson, 1994), with children under nine having difficulty using structural similarity for reasoning. In studies of older adults' reasoning, older adults also encoded more surface information. Viskontas, Morrison, Holyoak, Hummel, and Knowlton (2004) examined older adults' analogical reasoning using a people pieces analogy task, where source and target problems each contained a pair of human figures that could match on four dimensions: "gender, height, weight, and skin color." Participants needed to integrate the consistent relationship between the two figures in the source problem based on one or two dimensions specified below the pictures (only "same" or "different" relationships), then determine whether the consistency between the two figures in the target problem matched that of the source problem on the specified dimensions. Results showed that older adults encoded more surface information and processed relational (structural) information little or not at all (Viskontas et al., 2004). Additionally, visual working memory research found that older adults showed decline in binding surface information (color-shape) compared to remembering color alone (Isella, Molteni, Mapelli, & Ferrarese, 2015), and neural computational models showed that this age-related decline in structural extraction was related to increased noise in representations (Rhodes, Parra, Cowan, & Logie, 2017). Synthesizing previous research, different age groups seem to show different conclusions: studies where structural similarity dominated mostly involved young adults (Holyoak & Koh, 1987; Schnotz & Baadte, 2015), while children and older adults prioritized processing surface similarity (Viskontas et al., 2004). Therefore, the second question this study addressed is: In problem-solving based analogical reasoning tasks, do older and younger adults differ in their sensitivity to surface and structural information similarity? Based on previous findings, can increased surface similarity more effectively promote older adults' reasoning compared to structural similarity?

In summary, this study employed the problem-solving paradigm using story analogy tasks. By systematically manipulating the similarity of surface and structural information contained in source and target problems, we ensured that older and younger adults achieved equivalent encoding levels for source problems. The study aimed to investigate two questions: (1) Whether older adults' performance in problem-solving based analogical reasoning shows decline compared to younger adults; and (2) How surface and structural similarity affect reasoning quality across age groups: Is surface similarity more important for older adults, and structural similarity more important for younger adults?

2.1 Participants

We recruited 29 younger adults aged 20-26 years (age: M = 21.86, SD = 1.43; education: M = 14.48, SD = 1.02) from Beijing Normal University, and 32 healthy older adults aged 62-79 years (age: M = 69.09, SD = 5.11; education: M = 14.34, SD = 2.46) from communities in Beijing. None had brain diseases or neurodegenerative disorders such as Alzheimer' s disease. All participants had normal or corrected-to-normal vision and completed all tasks with valid data. The two groups showed no significant difference in education level [M_{young} = 14.48, M_{old} = 14.34; $t(42) = 0.29$, $p = 0.771$]. Since the analogical reasoning task involves semantic comprehension ability, we measured participants' semantic comprehension using the Vocabulary subtest of the Wechsler Adult Intelligence Scale (Chinese urban version). The groups also showed no significant difference in vocabulary comprehension [M_{young} = 17.17, M_{old} = 16.65; $t(59) = 0.94$, $p = 0.353$]. Participants received compensation after the experiment.

2.2 Experimental Materials: Analogical Reasoning Task

This experiment adopted the problem-solving based reasoning task following Gick and Holyoak' s (1983) paradigm. Participants were presented with a source problem and, after reading it, were required to complete the solution method for the target problem based on the source problem. During source problem reading, we ensured that all participants encoded at the higher-order relation level, that is, they summarized the underlying principle. We quantified surface and structural similarity levels by manipulating the number of matching surface and structural information features between target and source problems, and used correct completion of target problem solutions as the measure of reasoning quality. Source-target problem pairs were constructed based on Chinese idioms sharing the same higher-order rule, with four source problem stories, each generating four target problem stories with varying similarity. The higher-order relation information for source-target problems was expressed through four idioms: "a drop in the bucket," "Bo Le judges horses," "just right," and "Lord Ye' s love of dragons." Specific examples are shown in Table 1 .

Table 1 Example of source and target problems (A drop in the bucket)

Source Problem	Target Problem
Old Li was a woodcutter pushing a cart of firewood down the mountain. Feeling thirsty, he stopped to rest and took out his water flask to drink. Unexpectedly, the firewood cart caught fire with fierce flames. With no water source nearby, Old Li quickly splashed water from his flask onto the cart. But the water was too little, and the fire remained fierce. He could only watch his cart burn to ashes.	**High Surface Similarity, High Structural Similarity**: Old Zhang was a farmer who bought a cart of rock candy to take home. Feeling hot, he stopped to rest and took out some ice cubes. Unexpectedly, the weather was so hot that Old Zhang discovered the rock candy was melting in the sun. Too far from the shade, Old Zhang quickly poured the ice cubes in his hand onto the rock candy. {{{_}}{{}}}{{{_}}{{}}_}{{{}}{{}}_}. Old Zhang could only watch as all the rock candy in his cart melted in the sun.

Source Problem	Target Problem
	Low Surface Similarity, High Structural Similarity: Old Zhang was a farmer who bought a cart of rock candy to take home. Feeling hot, he stopped to rest and took out some ice cubes. Unexpectedly, a group of children gathered around, secretly taking rock candy to eat. With nothing else in hand, Old Zhang quickly poured the ice cubes in his hand onto the children to drive them away. {{{_}}{{}}}}{{{_}}{{}}_}{{{}}}{{}}}_}. Old Zhang could only watch as all the rock candy in his cart was eaten by the children. **High Surface Similarity, Low Structural Similarity**: Old Zhang was a farmer who had picked a cart of grass to take home for his livestock. Feeling hungry, he stopped to rest and took out a bowl of soup. Unexpectedly, a group of rabbits gathered around, eating the grass he had picked. With nothing else in hand, Old Zhang quickly splashed the soup from his hand to feed the rabbits. {{{_}}{{}}}}{{{_}}{{}}_}{_}. Old Zhang could only watch as all the grass in his cart was eaten up.

Source Problem	Target Problem
	Low Surface Similarity, Low Structural Similarity: Old Zhang was a farmer who had picked a cart of grass to take home for his livestock. Feeling hungry, he stopped to rest and took out a bowl of soup. Unexpectedly, the weather was so hot that Old Zhang discovered the grass was being scorched, emitting a pungent smell. Too far from the stream, Old Zhang quickly splashed the soup from his hand onto his hands. {{{_}}{{}}}{{{_}}{{}}_}{{{}}{{}}_}. Old Zhang could only watch as all the grass in his cart dried up.

Note: Bolded sections indicate surface or structural information matching the source problem; underlined sections indicate where participants, after a three-day delay and prompted that they could answer based on previously read content, wrote what might happen in the target problem. E = entities; F = first-order relation.

The correspondence between surface and structural information in the "a drop in the bucket" story example is shown in Table 2 .

Table 2 Similarity conditions of surface and structural features (e.g., A drop in the bucket)

Similarity Condition	Analogical Reasoning Story	Note
Similarity Condition	Analogical Reasoning Story	Note
E3F3	Source: Woodcutter, firewood, water; Target: Farmer, grass, soup	Numbers indicate matching surface and structural features between source and target. For example, E3F3 means 3 surface features match (entities including subject and object) and 3 structural features match (first-order relations including verbs describing entity relationships). Parentheses indicate alternative items used in target

Similarity Condition	Analogical Reasoning Story	Note
E1F3	Source: Woodcutter, firewood, water; Target: (Merchant), grass, (porridge)	
E3F1	Source: Woodcutter, firewood, water; Target: Farmer, (rock candy), soup	
E1F1	Source: Woodcutter, firewood, water; Target: (Merchant), (rock candy), (porridge)	

Filler materials were adapted from Gentner et al. (1993) and used as filler items. Each source and target problem pair shared a matching higher-order relation (HOR), with a filler-to-experimental material ratio of 4:1 (Catrambone, 2002). Filler materials served two purposes: (1) Preventing participants from directly associating source and target problems. Participants read numerous source stories, then after a delay read numerous target stories. Researchers examined whether source stories would cue target problem solving and whether such cuing effects came from specific source stories. (2) Enhancing ecological validity. When encountering different situational problems in real life, one needs to discover analogous situations from previously encountered problem contexts, but only some problems have previous solutions. Filler materials simulated this aspect of life experience.

Before the formal experiment, we evaluated the similarity of experimental materials to ensure effective matching of surface and structural information between source and target problems. Eleven younger adults and twelve older adults rated the similarity of word pairs (entities and first-order relations) from source and target stories and the similarity of the principles behind source and target stories (higher-order relations) on a 6-point scale (0 = "very dissimilar" to 5 = "very similar"), with higher scores indicating greater similarity. After modifications, both age groups rated entity pairs such as woodcutter-farmer (M = 3.68, SD = 1.16) as significantly more similar than dissimilar pairs like firewood-rock candy (M = 1.13, SD = 1.18; $t = 520.13$, $p < 0.001$), and both believed source and target problems shared the same higher-order relation (M = 3.75, significantly different from the midpoint of 2.5, $t = 16.64$, $p < 0.001$), meaning the extracted abstract rules were consistent. Material evaluation ensured the validity of surface and structural similarity manipulations. Participants who evaluated materials were homogeneous with but non-overlapping with the formal experimental sample.

2.3 Experimental Design

This experiment used a 2 (age group: older/younger) × 2 (surface similarity: high/low) × 2 (structural similarity: high/low) mixed design, with age group as a between-subjects variable and surface and structural similarity as within-subjects factors. The dependent variable was participants' completion of target problems, i.e., reasoning quality. Surface information referred to entities (abbreviated as E) appearing in stories, with surface similarity quantified by the number of matching entity pairs between source and target problems (e.g., woodcutter-farmer, firewood-grass). Three entity matches indicated high surface similarity (denoted E3), while one entity match indicated low surface similarity (E1). Structural information was divided into first-order relation information and higher-order relation information. This experiment primarily manipulated first-order relation similarity, using verbs in stories as first-order relations (abbreviated as F). Structural similarity was quantified by the number of matching predicate pairs (e.g., x catches fire, x gets scorched; x splashes y, x sprinkles y; Catrambone, 2002). For example, "Old Zhang sprinkles soup" could generate "Old Zhang sprinkles water" or "Old Li sprinkles soup." Three first-order relation matches indicated high structural similarity (F3), while one first-order relation match indicated low structural similarity (F1). Similarity relationships are shown in Table 2. Higher-order relation information remained consistent between source and target problems, meaning source and target problems shared the same abstract rule or causal structure (e.g., a drop in the bucket, overestimating one' s abilities). Thus, one source problem could generate four target problems with different similarity levels: E3F3, E1F3, E3F1, and E1F1. E3F3 represented the highest overall similarity between source and target problems, while E1F1 represented the lowest. Specific examples are shown in Table 1.

The entire reasoning task consisted of learning and testing phases. In the learning phase, participants studied 4 source problems plus 16 filler problems. The testing phase occurred after a three-day delay (Catrambone, 2002). In analogical reasoning, immediate analogies are discussed within the framework of working memory, whereas delayed matching involves long-term memory, so delay duration plays a role (Chen, Mo, & Honomichl, 2004). In this study, participants read numerous source stories during the learning phase, and after a delay we examined whether source stories would cue target problem solving and which type of similarity (surface or structural) would have stronger cuing effects. When determining the delay duration, Catrambone' s (2002) study used a 7-day interval, but even the highest similarity source problems had only a 0.31 recall rate, suggesting possible floor effects for older adults. This study set the delay interval at 3 days (Zhang & Wang, 1999). Results showed that younger adults did not exhibit ceiling effects and older adults did not show floor effects, making this interval appropriate. In the testing phase, participants completed 4 target problems and 16 filler problems. Each source problem corresponded to 4 target problems with different similarity levels. To prevent participants from repeatedly answering similar situational problems and reasoning repeatedly across 4 similarity conditions for the same scenario, we employed a Latin square design: during testing, each participant saw one of the four similarity-level target problems corresponding to each of the 4 source problems, ensuring each participant ultimately received 4 target problems at different similarity levels. For example, Participant A completed "a drop in the bucket" E3F3, "Bo Le judges horses"

E1F3, "just right" E3F1, and "Lord Ye' s love of dragons" E1F1; Participant B completed "a drop in the bucket" E1F1, "Bo Le judges horses" E3F3, "just right" E1F3, and "Lord Ye' s love of dragons" E3F1; Participant C completed "a drop in the bucket" E3F1, "Bo Le judges horses" E1F1, "just right" E3F3, and "Lord Ye' s love of dragons" E1F3; Participant D completed "a drop in the bucket" E1F3, "Bo Le judges horses" E3F1, "just right" E1F1, and "Lord Ye' s love of dragons" E3F3. Overall, participants received identical experimental treatments, only with different story scenarios corresponding to specific conditions.

2.4 Procedure

Learning Phase: Participants completed informed consent and demographic variables (age, gender, education). They studied a word list and were asked to memorize it as accurately as possible. Participants studied 20 source problems (4 target source problems, 16 filler materials) and summarized the higher-order structural information for each source problem, i.e., extracting the principle or moral of the story (Gick & Holyoak, 1983). For example, from the problem in Table 1 they would summarize "a drop in the bucket." To exclude effects of encoding stage differences and ensure participants had adequate time to read source problems, the experimenter also pointed out any problems participants misunderstood, guiding them to correctly understand story causal relationships and ensuring all participants encoded source problems at the higher-order relation level. Filler materials came from Gentner et al.' s research (Gentner et al., 1993).

Testing Phase (three days after pre-test): First, participants completed a word list recognition task as an index of long-term memory. Then, participants were randomly presented with 20 target problems (4 target problems, 16 filler problems). Instructions indicated that the new problems might be similar to previously studied problems and that participants needed to complete the target problems. Target problem completion served as the reasoning quality measure, scored as 0/1, with correct completion receiving 1 point and incomplete or incorrect answers receiving 0 points. The maximum score was 2 points per similarity condition. The parts to be completed in the 4 target problems did not involve experimentally manipulated entities or first-order relations. After completing all problems, the experimenter told participants that 4 stories (the 4 target stories) would be randomly selected, and participants needed to report whether they could recall the corresponding source stories from the learning phase and write them out. This checked whether participants completed target problems based on source problems. Retrieval quality for target source problems (an index of retrieving surface and structural information) was scored as the total number of surface and structural information pieces written from source problems, with each recalled entity or first-order relation receiving 1 point. For one source problem, the maximum surface information retrieval score was 3 points (3 entities), and the maximum structural information retrieval score was also 3 points (3 first-order relations). The study was conducted in a one-on-one interview format between experimenter and participant to ensure understanding of materials and task requirements.

3. Results

3.1 Age Characteristics of Reasoning Quality

The three-day interval between learning and testing involved long-term memory, but the two age groups showed no significant difference in post-test word recognition accuracy [$t(59) = -0.55$, $p > 0.05$]. Therefore, any differences in source retrieval analysis could not be attributed to poorer long-term memory in older adults.

Table 3 Reasoning quality under different similarity conditions (M ± SD)

Age Group	Surface Similarity	Structural Similarity	E3F3	E1F3	E3F1	E1F1
Younger	High	High	0.76 ± 0.44	0.69 ± 0.47	0.72 ± 0.39	0.76 ± 0.37
	Low	High	0.52 ± 0.28	0.48 ± 0.28	0.48 ± 0.35	0.45 ± 0.37
Older	High	High	0.28 ± 0.46	0.22 ± 0.42	0.31 ± 0.47	0.30 ± 0.31
	Low	High	0.38 ± 0.49	0.59 ± 0.50	0.38 ± 0.49	0.38 ± 0.25

A 2 × 2 × 2 ANOVA with surface and structural similarity as within-subjects variables and age group as a between-subjects variable revealed: First, a significant main effect of age [$F(1,59) = 13.29$, $p < 0.01$, $^{2} = 0.184$], with post-hoc comparisons showing the younger group significantly outperformed the older group ($MD = 0.25$, $p < 0.01$). Second, significant main effects of surface similarity [$F(1,59) = 17.62$, $p < 0.01$, $^{2} = 0.230$] and structural similarity [$F(1,59) = 16.74$, $p < 0.01$, $^{2} = 0.221$], indicating that similarity of surface and structural information between source and target problems significantly affected reasoning quality. Post-hoc comparisons showed E3 conditions were significantly better than E1 ($MD = 0.21$, $p < 0.01$), and F3 conditions were significantly better than F1 ($MD = 0.22$, $p < 0.01$). Thus, more similar information points led to better reasoning performance (see Table 3).

The three-way interaction between surface information, structural information, and age was significant, $F(3,177) = 4.45$, $p < 0.05$, $^{2} = 0.070$. Simple simple effects analysis showed: For younger adults, when structural similarity was high

(F = 3), reasoning quality did not differ significantly between high and low surface similarity conditions, F(1,59) = 0.38, p = 0.539, ^{2} = 0.006. However, when structural similarity was low (F = 1), reasoning quality in the high surface similarity condition was significantly better than in the low structural similarity condition, F(1,59) = 14.26, p < 0.001, ^{2} = 0.195, MD = 0.41 (see Figure 1 [Figure 1: see original paper] left). This indicated that structural information was more important for younger adults. The opposite pattern occurred for older adults, for whom surface information was more important: When surface similarity was low, there was no significant difference between high and low structural similarity conditions, F(1,59) = 0.59, p = 0.444, indicating that when surface similarity was insufficient, increased structural similarity did not improve reasoning quality. However, when surface similarity was high, higher structural similarity led to better reasoning quality, showing that older adults could benefit from increased structural similarity only when sufficient surface similarity was provided, F(1,59) = 4.24, p < 0.05, ^{2} = 0.067, MD = 0.22 (see Figure 1 right).

Figure 1 [Figure 1: see original paper] Reasoning quality of younger and older adults under different similarity conditions

3.2 Relationship Between Reasoning Quality and Retrieval Quality

Older adults relied more on surface similarity and younger adults more on structural similarity in reasoning quality. To test whether age group differences in reasoning resulted from differences in retrieving corresponding information from source problems, we analyzed participants' retrieval quality of surface and structural information from source problems under different similarity conditions. Retrieval quality under each condition is shown in Table 4 .

Table 4 Retrieval quality of source problems under different similarity conditions (M ± SD)

Age Group	Information Type	Surface Similarity	Structural Similarity	E3F3	E1F3	E3F1	E1F1
Older	Surface	High	High	1.21 ± 1.15	1.21 ± 1.01	0.93 ± 1.10	1.34 ± 1.05
		Low	High	1.69 ± 1.17	1.83 ± 0.89	1.07 ± 1.03	2.17 ± 0.89
	Structural	High	High	0.09 ± 0.39	0.44 ± 0.91	0.13 ± 0.42	0.44 ± 0.91
		Low	High	0.59 ± 0.98	0.59 ± 0.80	0.53 ± 0.92	0.91 ± 1.09

Age Group	Information Type	Surface Similarity	Structural Similarity	E3F3	E1F3	E3F1	E1F1
Younger	Surface	High	High	1.21 ± 1.01	1.34 ± 1.05	1.07 ± 1.03	2.17 ± 0.89
		Low	High	1.69 ± 1.17	1.83 ± 0.89	1.07 ± 1.03	2.17 ± 0.89
	Structural	High	High	0.44 ± 0.91	0.44 ± 0.91	0.53 ± 0.92	0.91 ± 1.09
		Low	High	0.59 ± 0.98	0.59 ± 0.80	0.53 ± 0.92	0.91 ± 1.09

Using retrieval quality scores for surface and structural information from source problems as dependent variables, we conducted separate 2 (surface similarity: high/low) × 2 (structural similarity: high/low) within-subjects ANOVAs on surface and structural retrieval quality within each age group. Results showed that in the older group, surface information retrieval quality improved with increased surface similarity [$F(1,31) = 8.34$, $p < 0.01$, $^2 = 0.212$] but changed little with increased structural similarity [$F(1,31) = 1.60$, $p = 0.215$], with no significant interaction [$F(1,31) = 1.518$, $p = 0.227$]. Structural information retrieval quality improved significantly with increases in both surface similarity [$F(1,31) = 12.35$, $p < 0.01$, $^2 = 0.285$] and structural similarity [$F(1,31) = 4.94$, $p < 0.05$, $^2 = 0.137$], with no significant interaction [$F(1,31) = 0.05$, $p = 0.829$]. Overall, surface similarity had a greater impact on older adults' retrieval quality, confirming that surface information was more important for older adults' reasoning quality.

In the younger group, surface information retrieval quality also improved with increased surface similarity [$F(1,28) = 7.93$, $p < 0.05$, $^2 = 0.221$] but changed little with increased structural similarity [$F(1,28) = 0.194$, $p = 0.663$], with no significant interaction [$F(1,28) = 0.11$, $p = 0.738$]. Structural information retrieval quality improved significantly with increases in both surface similarity [$F(1,28) = 6.057$, $p < 0.05$, $^2 = 0.178$] and structural similarity [$F(1,28) = 18.46$, $p < 0.01$, $^2 = 0.397$], with no significant interaction [$F(1,28) = 3.78$, $p = 0.062$]. Unlike the older group, increased structural similarity helped younger adults retrieve structural information from source problems, while increased surface similarity helped them retrieve surface information.

Correlation analysis between overall reasoning quality and overall retrieval quality across age groups revealed a significant positive correlation for younger adults, $r = 0.30$ ($p < 0.001$), and for older adults, $r = 0.37$ ($p < 0.001$), indicating that better source problem extraction was associated with better target problem answering.

4. Discussion

This study found overall that older adults performed worse than younger adults in analogical reasoning. Increased surface and structural similarity between source and target problems improved reasoning quality, consistent with many previous studies (Holyoak & Koh, 1987; Schnotz & Baadte, 2015). Surface similarity had a greater impact on older adults' reasoning quality, while structural similarity played a more important role for younger adults. Examining the effects of surface and structural similarity on older adults' analogical reasoning was a key focus of this study.

First, analogical reasoning showed age-related decline, consistent with previous research (Aichelburg et al., 2016; Bugaiska & Thibaut, 2015; Salthouse, 2005). However, the age difference in problem-solving based analogical reasoning found in this study was smaller than that in classical analogical reasoning tasks. Comparing the two paradigms, using younger adults' reasoning score standard deviations as a benchmark, we divided each age group' s reasoning score difference by the younger group' s standard deviation in that paradigm (Gerstorf, Ram, Hoppmann, Willis, & Schaie, 2011) to measure age differences in reasoning performance across task paradigms. We found that in classical analogical reasoning paradigms, older adults' scores were 3.20 SD lower than younger adults' (older: 1.08 ± 0.87; younger: 6.82 ± 1.79; Gao, Peng, Wang, & Wen, 2014) or 1.73 SD lower (older: 59.9 ± 9.2; younger: 79.1 ± 11.1; Salthouse, 1992b). In this study, older adults' scores were only 0.86 SD lower than younger adults' (older: 0.38 ± 0.25; younger: 0.62 ± 0.28). Thus, when using the more ecologically valid problem-solving paradigm, older adults' reasoning performance improved, narrowing the gap with younger adults. Overall, while this comparison method originates from cohort comparisons in longitudinal studies (Hülür, Ram, & Gerstorf, 2015; Schilling, 2005), cross-study comparisons are not rigorous and can only serve as rough explorations.

Second, regarding the role of information similarity, previous research found that both surface and structural similarity are important for successful analogical reasoning (Catrambone, 2002). This study confirmed this finding and further revealed that surface similarity was more important for older adults, while structural similarity was more important for younger adults. Analysis of source problem retrieval quality further confirmed these results: surface similarity could promote older adults' retrieval of surface information from source problems, thereby improving reasoning quality; both structural and surface similarity could promote younger adults' retrieval of structural and surface information from source problems, respectively, also benefiting their reasoning quality. In developmental research, Gentner (1988) proposed the concept of relational shift, where with age, individuals shift from relying on surface information to relying on structural information. This study found that in older adulthood, there is a similar reliance on surface information as in childhood, suggesting that development may have certain continuity and spiral progression characteristics.

Why do such age-related changes occur? First, older adults' cognitive characteristics may make them more sensitive to surface similarity. Morrison (2005) and Salthouse (1992b, 2005) analyzed research on reasoning aging and argued that reasoning requires storing and integrating numerous relations simultaneously in mind, meaning reasoning performance is constrained by working memory capacity. Compared to structural information, surface information is easier to retrieve (Catrambone, 2002), imposes less cognitive load, and is a more automated process than extracting structural information (Chen et al., 2004). Therefore, older adults show dependence on surface information. Similar results appear in children, who also show dependence on surface information and cannot utilize structural similarity, with the emergence of mental models playing an important role (Brown, Kane, & Echols, 1986). Second, motivation may play an important role in information processing. On one hand, older adults tend to simplify interactions with their environment and reduce the amount and complexity of information processing to conserve mental resources (Kossowska, 2007), thus using higher-order rules less to guide novel problem solving. On the other hand, older adults show higher need for cognitive closure, displaying hypervigilance—inefficiently processing more irrelevant information rather than schema-relevant information, i.e., retrieving more surface information (Kossowska, Jaśko, Bar-Tal, & Szastok, 2012). Finally, older adults' reliance on surface similarity in reasoning may relate to declines in vocabulary comprehension and integration abilities. In experimental materials, surface information was mostly nouns while structural information was mostly verbs. During reasoning, older adults needed to recall and write out source problems. Word recall research has found that older adults show a noun recall advantage, recalling nouns better than verbs, because verbs are more abstract than nouns, less clear and definite in meaning, and more difficult to integrate into sentences than nouns (Earles & Kersten, 2000).

Finally, regarding the relationship between reasoning quality and retrieval quality, this study found that retrieval quality correlated with reasoning quality in both age groups, indicating that better source problem extraction helped solve target problems. This is consistent with previous research showing that reasoning failure results from inability to access source problems in long-term memory or map entities and first-order relations from source problems (Chen et al., 2004). Analogical ability is a domain-general ability, and using long-term memory experience to solve current problems facilitates adaptation to environmental changes. In developmental research on analogical ability, the watershed for children to successfully demonstrate analogical ability lies in correctly representing relations, extracting information, ignoring irrelevant information, and maturation of the working memory system (Morrison & Cho, 2008). Brain imaging studies on reasoning development have also found that age-related involvement of the left anterior ventrolateral prefrontal cortex plays an important role in information extraction during reasoning, with activation in this region helping individuals better complete reasoning tasks (Bunge, Wendelken, Badre, & Wagner, 2005; Wright, Matlen, Baym, Ferrer, & Bunge, 2008). These studies all demonstrate that effectively retrieving source problem information is important for reasoning.

Older adults often encounter problems in daily life requiring transfer of experience from previous situations to new life scenarios. This study found that older adults' analogical reasoning depends more on surface similarity. Therefore, when designing products for older adults, to help them better understand product functions, first ensure sufficient surface similarity between new and source situations, which can help older adults effectively extract relevant information from source situations and achieve reasoning. Second, on the basis of sufficient surface information, others can prompt older adults in new situations to summarize rules based on existing knowledge and provide guidance on structural information. For example, when teaching older adults to use mobile phones, certain functions in WeChat, QQ, and Facetime are similar, but older adults still need guidance when using another app after learning one, depending on specific situations and unable to abstract rules. To help them understand similar functions across communication apps, first help them master surface information—recognizing universal meanings of mobile interface icons—then help them understand that long-pressing to send voice messages is common across different apps, helping them understand the underlying higher-order relations. Similarly, when designing different apps for older adults, similar interfaces should be created to reduce learning costs and improve their reasoning transfer abilities.

5. Limitations and Future Directions

This study has several limitations. First, materials could be further ecologically validated to be more life-relevant, such as daily life decision-making and interpersonal problems. Researchers have noted the role of social context in problem solving, such as whether problem contexts are social/non-social, individual traits, and relationship satisfaction (Hoppmann & Blanchard-Fields, 2011). When problem contexts involve interpersonal relationships, age-related variance might be further reduced (Thornton & Dumke, 2005). Second, this study still conducted reasoning in the same context and prompted participants to recall previously read stories. However, reasoning occurs automatically in real-life contexts. Future research could examine the transfer of learned rules to different problem contexts, investigating far transfer effects across contexts. Third, life-span comparison studies are needed, comparing older adults, younger adults, and children on analogical reasoning to obtain developmental characteristics across the life span.

6. Conclusions

1. Older adults show age-related decline in analogical reasoning.

2. Similarity of surface and structural information significantly affects reasoning quality; higher similarity leads to better reasoning quality.

3. Surface similarity is more important for older adults' reasoning and retrieval processes. Older adults can benefit from structural similarity only when sufficient surface information is provided.

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The role of surface and structural similarity in analogical reasoning aging: Based on the problem-solving paradigm

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Abstract

Analogical reasoning is a major form of abstract logical thinking. It refers to the transferring process of knowledge from one situation or field to another. To transfer successfully when facing new problems, it is important for the elderly to retrieve the appropriate sources of knowledge as quickly as possible. Additionally, the elderly rich in life experience are supposed to be the embodiment of wisdom, which is also helpful. Previous research about the elderly' s analogical reasoning mainly focused on the encoding stage, and, in most cases, the task paradigm was rigorous laboratory study. The task paradigm may have generated outcomes against participants'reactions in natural settings, causing reduced ecological validity and inability to present their real competence. The present study was based on the problem-solving paradigm rather than a laboratory-based experiment. We aimed to figure out whether the elderly retrograde in the retrieval of source problems and whether there exist age differences in the usage of surface information and structural information. The encoding quality between the old and young participants was ensured to be identical.

Twenty-nine young adults (age: M = 21.86, SD = 1.43) and thirty-two old adults (age: M = 69.09, SD = 5.11) participated in the experiment. This study used a mixed design in which age group (old/young) was a between-subjects variable and surface similarity (high/low) and structural similarity (high/low) were within-subjects variables. There were two phases included in the whole procedure. During the learning phase, participants learnt twenty source stories and summarized the higher-order relation of each. Three days later, twenty other target stories were presented in which participants were to figure out how to solve the problems with the hints they recalled from the source stories learnt three days ago. The performance of reasoning (quality of solving the target problem according to the source problem) and retrieving (quantity of surface and structural information retrieved) were the dependent variables.

The results showed that the elderly experienced analogical reasoning aging. To be specific, they relied more on the surface feature similarity than did the younger adults. As for surface and structural information, the more the information was provided, the better was their reasoning. It was beneficial to both age groups in reasoning when the surface and structural similarity increased, which indicated that the reasoning of the elderly and young people could benefit from better retrieval to the source problems. As for interaction effect, for the elderly in lack of surface information, increasing structural similarity would not enhance their reasoning quality. When there was enough surface and structural information, they performed the best. It implied that the elderly could benefit from structural similarity only on the condition that enough surface information was given. When retrieving information from source problems, surface feature exerted an across-information-type promotion effect on retrieval quality. However, the increase in structural information could only help the elderly to improve their retrieval in structural information. As for the younger adults, structural features and surface features were conducive to their retrieval of homogeneous information. With regard to the relation between retrieval quality and reasoning performance, the correlation was significant in both age groups. It enlightened us that people who cannot reason correctly were probably poor in retrieval.

To improve the performance of the elderly in analogical reasoning, we can increase the transmission of surface features, such as designing mobile phone apps with similar interfaces, which can reduce their learning cost. Further studies should focus on designing more realistic contexts as well as delving into the process of how far transfer of learning happens.

Key words: analogical reasoning; transfer; problem solving paradigm; surface similarity; structural similarity

Note: Figure translations are in progress. See original paper for figures.