Attention Selection Mechanism Based on Feature Relations

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Abstract

Selective attention is a key mechanism through which the brain filters external information. Traditional theories posit that individuals primarily guide attentional selection based on the feature values of stimuli. However, recent studies have found that in many contexts, individuals' attention allocation depends on the relative feature relationships between stimuli. This "feature-relationship-based" attentional selection mechanism applies to contingent attentional capture and experience-driven attentional selection, and differs from the "feature-value-based" attentional mechanism in terms of temporal dynamics and spatial globality. Future research should integrate multi-dimensional evidence to reveal the cognitive neural mechanisms underlying "feature-relationship-based" attention, expand its research scope to other relational attributes (such as spatial relationships and social relationships), and deeply explore the application potential of this mechanism in practical scenarios such as clinical and engineering contexts.

Full Text

Feature-Relationship-Based Attentional Selection Mechanism

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Abstract

Selective attention is the critical mechanism through which the brain filters external information. Traditional theories posit that individuals primarily guide attentional selection based on the feature values of stimuli. However, recent research has revealed that in many contexts, attentional allocation depends on

the relative feature relationships between stimuli, rather than on specific feature values. This "feature-relationship-based" attentional selection mechanism applies to both contingent attentional capture and experience-driven attentional selection, and differs from "feature-value-based"attentional mechanisms in terms of temporal dynamics and spatial globalness. Future research should integrate multidimensional evidence to uncover the cognitive and neural mechanisms underlying feature-relationship-based attention, expand its scope to other relational attributes (e.g., spatial and social relationships), and explore its practical applications in clinical and engineering contexts.

Keywords: selective attention, feature relationship, contingent attentional capture, experience-driven attention

In real-world contexts, relational information is ubiquitous [**?**]. This includes feature relationships between objects (e.g., an apple is redder than an orange), spatial relationships (e.g., an apple on a shelf), and social interaction relationships (e.g., face-to-face communication). From infancy, humans gradually develop the capacity to construct and utilize such relational information [**?**, **?**], a capability considered foundational to human cognition [**?**]. Existing theories and research indicate that the brain automatically processes relative relational information between stimuli. Examples include Gestalt principles of perceptual organization (proximity, similarity, continuity), object recognition based on relative physical attributes (relative color, relative size) [**?**], and cognitive maps constructed through relative positions of different landmarks [**?**].

However, previous research has primarily focused on how individuals selectively process specific information among multiple stimuli, largely neglecting the role of inter-stimulus relational information in attentional selection. Taking feature-based attention as an example, traditional attention theories posit that it involves allocating attentional resources based on stimulus feature dimensions (e.g., color) or feature values (e.g., red). This "feature-value-based" attentional effect can be explained by the feature similarity gain model [Figure 1: see original paper]A, which predicts that the more similar a stimulus' s feature value is to the target, the stronger the observed attentional effect [**?**]. Recent studies have challenged this view, finding that individuals often guide attention based on feature relationships between stimuli (e.g., "redder") [**?**, **?**]. This "feature-relationship-based" attentional effect depends on a stimulus' s relative relationship with other stimuli in its context; when a stimulus' s relative feature matches the target' s relative relationship, attentional effects are enhanced [Figure 1: see original paper]B.

[Figure 1: see original paper] Attentional tuning curves. In this simulated scenario, the target feature is set to orange (0°). The horizontal axis represents the difference between the presented stimulus and the target feature, while the vertical axis represents a measurable index of attentional change (either behavioral or neural activity). (A) Feature similarity gain model. According to this model, the more similar a stimulus is to the target feature value (difference closer to 0°), the stronger the attentional gain it elicits. (B) Feature relationship model.

Assuming distractor stimuli are positive values (greater than 0°) and the target' s relative relationship is "redder," this model predicts that attentional effects are enhanced when a stimulus' s relative relationship matches the target' s relative relationship (i.e., the stimulus is also relatively redder), as shown in the right curve from -45° to 0°.

Recent attention theories have begun to incorporate the role of feature-relationship-based attention in information selection. For instance, Wolfe [?] incorporated "feature-relationship-based attentional mechanisms" into the latest Guided Search theory for the first time. Yu et al. [?] further proposed that "feature-relationship-based attentional templates" play a crucial role in early information processing, rapidly helping us identify candidate targets and thereby improving search efficiency. However, compared to the extensive literature reviews on "feature-value-based attentional mechanisms" both domestically and internationally (e.g., [?, ?, ?, ?]), current research on "feature-relationship-based attentional mechanisms" lacks systematic synthesis. To fill this gap, this article aims to review research progress on feature-relationship attentional mechanisms and analyze their key differences from traditional feature-value attention theories. We summarize recent developments, theoretical advances, and application prospects in this field to provide insights for related research.

The Role of Feature Relationships in Different Attention Types

Feature-relationship-based attentional selection primarily focuses on two aspects: first, goal-driven contingent attentional capture, which refers to the phenomenon where stimuli associated with target features automatically capture attention independent of their physical salience [?]; and second, experience-driven attentional capture, where stimuli related to past experience or learning but irrelevant to the current task automatically capture attention [?]. Below, we examine the role of feature relationships in these two types of attentional capture in detail.

Singleton Feature-Based Attention

In research on contingent attentional capture, the cueing paradigm is a classic experimental approach [Figure 2: see original paper]. In this paradigm, a task-irrelevant cue display containing a salient feature stimulus (a pop-out singleton) is presented before the target stimulus. Results show that when the singleton' s feature value matches the target stimulus' s feature value, the cue captures attention [?], demonstrating that task goals modulate singleton-induced capture effects through top-down attention [?]. However, Becker et al. [?] obtained different results using a similar paradigm. As shown in [Figure 2: see original paper]A, participants searched for an orange target among yellow distractors. The target had both a specific orange feature value and the feature relationship of being "redder" relative to the distractors. According to feature-value attention theory, one would expect participants to prioritize orange stimuli in the cue display that match the target’ s feature value. However, results showed attentional priority was biased toward stimuli matching the target’ s feature relationship (redder) rather than its specific color, supporting feature-relationship-based attention theory. Specifically, when red and orange served as singletons in separate cue displays and both were redder than other stimuli, they elicited equivalent capture effects. When red and orange appeared together in the same cue display, attention prioritized the red stimulus because it was redder than orange, demonstrating the dominant role of target feature relationships in attentional guidance. Importantly, researchers included a green cue with the same physical salience as the red cue but found it did not capture attention, ruling out physical salience as an alternative explanation. Subsequent studies using various attention paradigms (e.g., additional singleton paradigm: presenting a singleton distractor in the search display to compare capture effects across different feature values and relationships) and stimulus dimensions (e.g., size, shape) have provided converging evidence for feature-relationship-based attention [?, ?]. Eye-tracking research has further revealed that initial saccades are more likely to be directed toward singleton distractors matching the target’ s feature relationship than those matching its feature value [?, ?]. EEG studies show that singletons matching the target’ s feature relationship elicit stronger and earlier N2pc components compared to those matching the target’ s feature value [?], further supporting the role of feature relationships in early attentional processing.

[Figure 2: see original paper] The cueing paradigm for feature-based attention. (A) In the singleton feature search task, participants searched for a singleton feature (orange) in the search display. (B) In the conjunction feature search task, participants searched for a target defined by a specific feature combination (e.g., cyan and medium size). In both tasks, attentional effects induced by cues were measured by comparing behavioral performance between valid and invalid cue conditions. By further comparing attentional effects under feature-relationship versus feature-value matching conditions, researchers examined whether cue-induced effects better matched predictions from feature-value or feature-relationship attention theories. Adapted from Becker et al. [?, ?].

While these studies provide initial support for feature-relationship-based attention theory, alternative explanations have been proposed. For instance, optimal tuning theory [?, ?] suggests that the attentional system may optimize search efficiency by increasing discriminability between targets and distractors. Computational modeling indicates that when target and distractor feature values are similar, the attentional template’ s target feature value may shift away from the distractor feature value to expand the neural response difference between them (i.e., increase signal-to-noise ratio). In a visual search task where participants searched for a 55° line segment among 50° distractors (reporting the number at the target location) while probe trials presented lines at various orientations (30°, 50°, 55°, 60°, and 80°), participants more frequently reported the number corresponding to the 60° stimulus, suggesting the attentional template shifted from the target orientation (55°) away from the distractor (50°). Notably, this theory can also explain findings from feature-relationship-based attention studies. In Becker et al.' s [?] study, where the target (orange) and distractors (yellow-orange) were highly similar, the attentional template might shift toward red to better discriminate target from distractors. This shift would cause red stimuli to produce stronger capture than the actual target color (orange), consistent with Becker et al.' s results. Although optimal tuning theory and feature-relationship theory share similarities, they differ critically: optimal tuning theory predicts shifts in attended feature values but still follows the principle of feature similarity [Figure 1: see original paper]A. To distinguish these hypotheses, Becker et al. [?] used a cueing paradigm where participants searched for an orange target among gold distractors (redder than gold) and compared capture effects across cue conditions with identical feature relationships (redder) but different cue values (gold singleton among yellow vs. red singleton among orange). According to optimal tuning theory, to discriminate the orange target from gold distractors, participants would shift their attentional template toward red, making red cues more likely to capture attention. Feature-relationship theory predicts that any singleton satisfying the "redder" relationship, whether gold or red, should capture attention. Results supported the latter, further confirming the role of feature relationships in goal-driven attention.

Conjunction Feature-Based Attention

Although singleton feature-based attention research reveals the importance of feature relationships in goal-driven attention, the theory' s applicability has two limitations: first, these studies focus only on single feature dimensions (e.g., color or size); second, results from singleton paradigms reflect attentional modulation of physically salient stimuli. To examine whether feature-relationship-based attention theory generalizes to more typical attentional contexts, researchers have turned to conjunction search tasks [?, ?]. In these tasks, search targets are defined by combinations of two features (e.g., a red vertical line). Such targets involve multiple feature dimensions and are not physically salient relative to distractors (e.g., red horizontal lines, green vertical lines) [?]. In Becker et al. [?], participants searched for targets defined by combinations of two feature dimensions (e.g., medium size, cyan color) and judged their orientation. Before the search display, two types of task-irrelevant cue displays were presented: (1) cues matching the target' s feature-relationship combination but not necessarily its exact feature values; (2) cues matching the target' s feature-value combination but not necessarily its feature relationships. Results showed that when cues fully matched the target' s feature relationships [Figure 2: see original paper]B, all relationship-matched cue condition, they elicited significant attentional attraction regardless of feature-value match; conversely, cues matching feature values but not feature relationships [Figure 2: see original paper]B, all feature-value matched cue condition failed to elicit attentional effects. EEG studies using similar paradigms found that cues consistent with the target' s feature relationships could elicit N2pc components, while those inconsistent could not. Subsequent research examining different feature dimension combinations (e.g., size and color) and combinations of feature relationships and values [?] found similar feature-relationship-based attentional capture. In summary, this "feature-relationship-based attention effect" is not limited to single feature dimensions and does not depend on stimulus-driven attentional mechanisms.

The Role of Feature Relationships in Experience-Driven Attentional Capture

Recent research demonstrates that learning experience can independently influence attentional allocation. Previously learned stimuli can automatically capture attention even when irrelevant to the current task (see reviews by [?, ?]). Experience-driven attention includes inter-trial priming effects, reward history (stimuli associated with reward feedback in past experience), and selection history (stimuli that served as targets in past experience). Among these, inter-trial priming effects primarily reveal the impact of brief experience on attention, while reward and selection history reflect more sustained influences over longer periods. Reward history and selection history may involve different mechanisms in driving attention [?]: the former primarily relies on Pavlovian conditioning mechanisms [?], whereas the latter is more based on habitual attention allocation [?].

Inter-Trial History-Based Attention Feature-relationship attention mechanisms originally emerged from research on inter-trial priming effects. Inter-trial priming refers to how responses on previous trials influence performance on current trials. In singleton search tasks, for example, behavioral performance is better when target and distractor features remain the same across consecutive trials compared to when they change [?]. Traditionally, this effect was attributed to facilitation from repeated target feature values or inhibition from repeated distractor feature values. However, Becker [?, ?] proposed an alternative explanation: relational priming theory, which suggests that inter-trial priming stems from the feature relationship between target and distractors, not from their specific feature values. To test this hypothesis, researchers designed two experimental conditions: a "feature-relationship repetition group" and a "feature-relationship change group." In the repetition group, distractor feature values remained constant while target feature values repeated or changed, but the target-distractor feature relationship stayed the same. Conversely, in the change group, the target-distractor feature relationship changed. According to the feature-value priming hypothesis, priming should occur whenever target feature values remain unchanged; according to the feature-relationship priming hypothesis, priming should only be observed in the feature-relationship repetition group. Results supported the latter, indicating that target feature value repetition alone is insufficient to produce priming and that the key determinant is repetition of the feature relationship between target and distractors across trials.

These experiments also examined whether distractor feature value suppression influences inter-trial priming. Unlike the "feature-relationship change group" (where only feature relationships could change while distractor values remained constant), a "target-distractor swap group" was created where both distractor feature values and relationships could change. If suppression of distractor feature values affected priming, then priming from repeated (vs. changed) distractor values should enhance priming beyond that induced by target feature relationships, resulting in stronger effects in the swap group than in the relationship change group. However, results showed no significant difference in priming magnitude between these groups, indicating that distractor feature value repetition alone does not affect priming. This series of experiments demonstrates that inter-trial priming depends primarily on the consistency of feature relationships between targets and distractors across trials, rather than on repetition of specific feature values, further highlighting the central role of feature relationships in attentional allocation.

Reward and Selection History-Based Attention Past experience in the form of reward history (e.g., reward-associated features) and selection history (e.g., high-probability target features) can independently modulate attentional allocation [**?**, **?**, **?**, **?**, **?**, **?**]. Such research typically employs separate training and test phases: participants gain experience during a training phase by performing target tasks, and the test phase uses tasks unrelated to the training targets to examine how prior experience influences current attentional allocation.

Some studies have investigated whether feature-relationship-based attention mechanisms apply to selection history-driven attention. In Liao et al. [**?**], target and distractor feature values remained constant during training (e.g., orange targets, red distractors). In the subsequent test phase, the search display contained four stimuli: two red stimuli (same color), one orange stimulus (feature-value match), and one yellow stimulus (feature-relationship match). The target was a shape singleton, with color being task-irrelevant. Results showed that when the feature-relationship-matching stimulus (yellow) served as the target, participants' search speed was faster than for targets of other colors, demonstrating that selection history influences current attention based on feature relationships rather than feature values.

Unlike selection history, research on reward history employs training stimuli that serve as targets with equal probability but differ in their predictive value for reward. For example, during training, red stimuli might predict high monetary reward with 80% probability while yellow stimuli predict it with only 20% probability [Figure 3: see original paper]A. Traditional views suggest that reward history modulates attention in a feature-value-based manner [**?**], but Chen et al. [**?**] found that reward history can also modulate attention through a feature-relationship-based mechanism. Using a similar training method [Figure 3: see original paper]A, the test phase employed an additional singleton paradigm where the singleton' s feature value remained constant (e.g., orange) but its feature relationship relative to other stimuli varied (redder or yellower). Results showed that when high reward was associated with red, attentional capture was enhanced for singletons whose color was "redder" relative to other stimuli. In subsequent experiments, researchers pitted feature values against feature relationships. As shown in [Figure 3: see original paper]B, in terms of feature relationships, a reddish-orange singleton was "yellower" among red stimuli, while a yellowish-orange singleton was "redder" among yellow stimuli; however, in terms of feature values, the reddish-orange was closer to the high-reward-associated red than the yellowish-orange. According to feature-value modulation theory, the reddish-orange stimulus should produce stronger capture than the yellowish-orange stimulus, whereas feature-relationship modulation theory predicts the opposite. Results again showed that singletons whose feature relationships matched high reward (redder, i.e., yellowish-orange among yellow stimuli) produced stronger attentional capture. These findings indicate that reward history-driven attentional advantages can transfer to novel stimuli and contexts based on inter-stimulus feature relationships, independent of learned feature values.

[Figure 3: see original paper] The modulatory effect of reward (monetary) on feature-relationship-based attention. (A) During training, a visual search task was used to establish associations between reward and features (e.g., high reward—red, low reward—yellow). (B) During testing, an additional singleton paradigm was used to manipulate both the singleton' s feature values (e.g., reddish-orange and yellowish-orange) and feature relationships (yellower or redder). In the bar graph on the right, blue and orange bars represent behavioral performance (reaction times) under high and low reward conditions for feature-value and feature-relationship matching conditions, respectively. Adapted from Chen et al. [?].

These studies demonstrate that past learning experience can automatically modulate current attentional selection by recognizing feature relationships between stimuli. This capability enables individuals to apply these experiences to new contexts, guiding current attentional selection by identifying stable inter-stimulus relationships. Compared to the default "feature-value-based" explanations commonly assumed in experience-driven attention research [?], this mechanism is better suited to dynamic real-world environments and may thus help us better understand attentional control mechanisms in complex settings. However, current research lacks multidimensional neuroimaging or brain stimulation evidence, limiting our understanding of the underlying neural mechanisms. Future studies should combine EEG, fMRI, or transcranial magnetic stimulation to investigate the dynamic changes and key brain regions involved in feature-relationship-based modulation of experience-driven attention.

Dissociations Between Feature-Relationship-Based and Feature-Value-Based Attention

It is important to note that feature-value-based and feature-relationship-based attentional mechanisms are not mutually exclusive; individuals can flexibly select different attentional control modes according to task demands [?]. For example, in conjunction search tasks, individuals can adopt a feature-value matching mode in one stimulus dimension (e.g., red target) while using a feature-relationship matching mode in another dimension (e.g., larger target), switching between the two mechanisms as needed [?]. Chen et al. [?] also found that when reward-associated stimuli had opposing feature values and relationships (e.g., training participants to search for a reddish-orange target among red stimuli with high reward feedback, where the high-reward-associated feature relationship was "yellower" but the feature value biased toward red; then in testing presenting a reddish-orange singleton among orange stimuli where the singleton' s feature value matched high reward but its feature relationship matched low reward), this opposing association eliminated reward-driven attentional effects. This suggests that during training, participants simultaneously learned associations between reward and feature values as well as between reward and feature relationships. What, then, distinguishes these two attentional mechanisms? This article provides an in-depth comparison from temporal and spatial perspectives to inform understanding of which mechanism dominates attentional selection under different circumstances.

Temporal Dissociation

Behavioral and eye-movement studies provide evidence for temporal dissociations between these attentional mechanisms. For example, research using the additional singleton paradigm presented a shape-singleton distractor during visual search, manipulating both (1) the color feature similarity between the distractor and target stimulus, and (2) whether the distractor's feature relationship relative to non-singleton stimuli (e.g., redder or yellower) matched the target' s feature relationship (e.g., redder) [?]. In a specific experiment using an orange target (redder than non-singletons), as distractor color gradually shifted from orange toward red, its feature similarity to the target (orange) decreased while its feature relationship remained "redder." Similarly, as distractor color shifted from orange toward yellow, similarity decreased while the feature relationship remained "yellower." Using proportion of first saccade as an early attentional orienting index, results showed that distractors sharing the target' s feature relationship captured more initial eye movements than those with different relationships, independent of feature similarity. Additionally, probe trials examined the feature values participants used to identify targets by presenting stimuli with different feature values after some search trials and asking participants to identify the target' s feature value. Results showed that participants' misreporting of distractors increased with their similarity to the target but was unaffected by whether the distractor' s feature relationship matched the target' s. A modeling study using similar methods found that feature-relationship-based models better explained early attentional stages (first saccade proportion), whereas feature-value-based models were more advantageous for later processing stages (dwell time) [?].

Collectively, these studies suggest that feature-relationship-based and feature-value-based attention serve distinct roles at different information processing stages. This temporal dissociation may correspond to changing demands during visual search: rapid screening of potential targets initially (emphasizing speed), followed by precise discrimination of whether the selected stimulus is the target (emphasizing accuracy).

Spatial Scope Dissociation

Feature-value-based attentional effects are characterized by spatial globalness [?], meaning they are not limited to attended locations but can spread to unattended spatial locations. To investigate whether feature-relationship-based attention shares this spatial globalness, researchers employed rapid serial visual presentation (RSVP) tasks [?, ?], presenting letter streams at the center of the screen to focus spatial attention within a small central region (<1.5°) while presenting different distractors in the peripheral visual field, manipulating whether these distractors matched the target in feature value or feature relationship. If peripheral distractors triggered attentional shifts, they would impair target identification accuracy at the central location (i.e., attentional blink). Results showed that distractors matching the target's feature value produced attentional blink effects, consistent with spatial globalness. However, distractors matching the target' s feature relationship did not produce attentional blink, suggesting that feature-relationship-based attention may lack spatial globalness.

An alternative interpretation is that feature-relationship-based attentional effects might not be unable to spread to unattended locations but rather constrained by the task-defined attentional window. To test this, researchers presented RSVP tasks at three locations simultaneously to expand the attentional window while manipulating distractor appearance at non-target locations within the window [?]. Results showed that distractors matching the target' s feature relationship produced stronger attentional blink effects than those matching feature values. These findings indicate that feature-relationship-based attention can spread to non-target spatial locations, but its spread is constrained by attentional window size, whereas feature-value-based attentional globalness is unaffected by window size. This difference may stem from the fact that extracting feature relationships requires inter-stimulus comparisons, a process demanding more attentional resources and thus less likely to spread beyond the attentional window.

Subsequent research found that under specific conditions, feature-relationship-based attention can also exhibit globalness. For example, Hua et al. [?] found that when target feature values were variable and targets had to be identified based on feature relationships (e.g., the target was always greener than other stimuli), peripheral distractors matching the target' s feature relationship could still capture attention. This suggests that when feature relationships are necessary for target identification, the resulting attentional mechanism exhibits globalness and is not constrained by attentional window size. This implies that both feature-relationship-based and feature-value-based attention possess globalness, but their priority inside versus outside the attentional window can be strategically adjusted according to task demands. Specifically, when stimulus feature relationships are essential for task completion, the resulting attentional effects are global; conversely, when feature relationships are task-irrelevant, their attentional priority outside the attentional window is relatively reduced.

Summary and Outlook

Previous research has extensively examined the role of feature relationships across different attention types using behavioral experiments, eye-tracking, and EEG. Unlike traditional "feature-value-based" attentional mechanisms, "feature-relationship-based" attentional mechanisms consider not only specific stimulus physical attributes but also contextual information. These two feature attention mechanisms are not mutually exclusive but may differ in their temporal dynamics and spatial distribution during information processing. Notably, feature-relationship-based attentional mechanisms align with the recently proposed "Good-enough" visual search theory [**?**, **?**]. This theory posits that people often do not rely on the "single, veridical" attentional template postulated by traditional theories but instead use a coarser, more abstract template sufficient for rapidly locating potential targets (called an attentional guidance template). Recent research has provided empirical support for such guidance templates at the neural level [**?**, **?**]. Within this theoretical framework, feature-relationship-based attentional templates are considered important representations that guide attention primarily during early processing stages. In contrast, feature-value-based templates focus more on encoding stimulus physical attributes and assist decision-making processes during later stages, responsible for fine-grained discrimination between selected stimuli and targets (called target matching templates). This functional dissociation along the temporal dimension may represent a neural computational strategy that optimizes the speed-accuracy tradeoff during information processing.

Despite substantial empirical research on feature-relationship-based attentional selection, our understanding of its cognitive and neural mechanisms remains limited. For example, the neural mechanisms underlying feature-relationship-based attention (key brain regions and their interactions) are not yet clear, and whether this relational attention mechanism generalizes to other stimulus dimensions requires further empirical investigation. Addressing these issues, future research should focus on two main aspects: (1) At the theoretical level, combining neural techniques (e.g., brain imaging) to reveal the neural basis of feature-relationship-based attention and its similarities and differences with traditional feature-value mechanisms. To further investigate whether this mechanism reflects a general principle of how the brain processes relational information, future studies should expand to other types of relational information (e.g., social relationships, spatial relationships) and other cognitive processes (e.g., working memory). (2) At the application level, findings from basic research can inform clinical diagnosis and treatment of mental disorders and engineering applications. The following sections discuss these directions.

Investigating the Neural Mechanisms and Generalizability of Feature-Relationship-Based Attention

Current research on feature-relationship-based attention has focused primarily on behavioral levels, with only a few studies using EEG to probe the temporal characteristics of associated neural activity [?, ?]. Future research should incorporate brain imaging techniques to investigate the neural mechanisms of feature-relationship-based attention and its similarities and differences with feature-value-based attention.

Two hypotheses currently exist regarding the neural mechanisms of feature-relationship-based attention. First, animal electrophysiology studies suggest that the brain may contain neurons that represent relational information, encoding relative rather than absolute feature values. For example, activation of color-opponent cells in early visual cortex reflects a comparison of color information from central and peripheral cone inputs rather than selective responses to specific feature values [?, ?], suggesting that feature-relationship coding may occur in sensory cortex. During attentional selection, higher-level frontoparietal networks may modulate activity in sensory cortex neurons selective for feature relationships through top-down feedback, thereby enhancing attentional processing of feature-relationship-matching information. However, whether such "relational neurons" exist in human sensory cortex remains to be directly demonstrated. Future research should explore this using higher-precision neural measurement techniques (e.g., ultra-high-field MRI; [?, ?]). Second, some propose that the posterior parietal cortex may be the optimal candidate region for encoding feature-relationship-based attention. This region not only encodes relative physical attributes of stimuli in physical space and semantic relationships in conceptual space [?] but also represents attentional priority maps [?]. This suggests that feature relationships and attentional signals may converge in posterior parietal cortex to compute priority. Given that feature relationships reflect abstract representations of stimuli, they may be encoded in higher-level cortex in a simplified, low-dimensional neural representation [?, ?]. These hypotheses can be distinguished using transcranial magnetic stimulation to causally examine how suppressing sensory cortex versus posterior parietal cortex affects feature-relationship-based attentional effects.

Current research on feature-relationship-based attention mechanisms has focused primarily on basic stimulus dimensions (color, shape, etc.), but whether this mechanism applies to stimuli of varying complexity (e.g., spatial relationships, social relationships) remains unclear. Previous studies show that people automatically process spatial relationships between different objects [?, ?] and social relationship information of varying complexity (e.g., face-to-face stimuli, cooperative or competitive relationships; [?, ?, ?]), and this automatic processing causes related stimuli to be prioritized in competition. Moreover, past experience influences not only feature-relationship-based attention but also the processing of other relational information. For example, with social experience and cognitive development, individuals' attentional preferences for social relationship information change. Research shows that 7-month-old infants preferentially attend to "back-to-back stimuli" over "face-to-face stimuli," whereas 5-year-old children and adults show the opposite preference [?]. Future research should also extend feature-relationship-based attention mechanisms to other cognitive processes such as working memory. Studies indicate that physical attribute relationships between stimuli (e.g., dynamic relationships, color relationships) are automatically encoded into working memory [?, ?], and information containing social relationships (face-to-face stimuli) is automatically chunked and stored in working memory [?, ?, ?]. This suggests that different types of relational information may share similar processing mechanisms in working memory.

Exploring Practical Applications of Feature-Relationship-Based Attention

Future research should also apply feature-relationship-based attention mechanisms to clinical diagnosis and intervention for mental disorders or psychological conditions. Research shows that various mental disorders involve abnormal processing of relational information. For example, compared to healthy individuals, autism spectrum disorder patients show clear deficits in remembering relationships between objects (e.g., spatial, sequential relationships) [?, ?, ?], and post-traumatic stress disorder patients also exhibit abnormal spatial relationship memory [?]. Although these studies focused on memory processes, given the important role of selective attention at all stages of memory processing [?], these findings may reflect difficulties in prioritizing relational attributes during information processing in these disorders. Therefore, the degree to which individuals attend to relational information could serve as an auxiliary diagnostic indicator for mental illness. Additionally, research shows that attentional bias training can improve social attention in autism patients [?] and reduce symptom severity in PTSD patients [?]. Future research could therefore develop attentional bias training paradigms targeting relational information processing to provide potential clinical interventions.

The advantages of feature-relationship-based attention may also inspire engineering applications. First, feature-relationship-based attention mechanisms offer greater stability. In natural environments, objects' specific feature values (e.g., brightness, color) are susceptible to environmental influences, whereas their relationships with the environment are typically more stable. For example, absolute height perception of a building may vary with viewing angle, but its relative attribute as the tallest building in an area remains constant. Second, as abstract information, feature relationships possess cross-context transferability. For example, perception of layout composition in photography can be applied across different scenes. Based on these advantages, feature-relationship-based attention could optimize artificial intelligence algorithms and human-computer interaction design. In intelligent medical imaging diagnosis [?, ?, ?], diagnostic efficiency could be improved by separating localization and identification stages: the localization stage could prioritize feature relationships (e.g., relative brightness between regions) to narrow search scope, while the identification stage could focus on feature values (e.g., volume, density) to improve discriminative accuracy. In human-computer interaction design [?, ?], maintaining consistency of feature relationships between key elements and their surroundings (e.g., preserving key elements' feature relationships when switching between day/night modes) could reduce attentional costs from information changes and enhance user experience and cognitive efficiency. Future research should further explore the information processing advantages of feature-relationship-based attention in complex environments and expand its application to more engineering contexts.

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Selective attention based on feature relationship

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