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Internal attention to features in visual short-term memory guides object learning

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ABSTRACT

Attending to objects in the world affects how we perceive and remember them. What are the consequences of attending to an object in mind? In particular, how does reporting the features of a recently seen object guide visual learning? In three experiments, observers were presented with abstract shapes in a particular color, orientation, and location. After viewing each object, observers were cued to report one feature from visual short-term memory (VSTM). In a subsequent test, observers were cued to report features of the same objects from visual long-term memory (VLTM). We tested whether reporting a feature from VSTM: (1) enhances VLTM for just that feature (practice-benefit hypothesis), (2) enhances VLTM for all features (object-based hypothesis), or (3) simultaneously enhances VLTM for that feature and suppresses VLTM for unreported features (feature-competition hypothesis). The results provided support for the feature-competition hypothesis, whereby the representation of an object in VLTM was biased towards features reported from VSTM and away from unreported features (Experiment 1). This bias could not be explained by the amount of sensory exposure or response learning (Experiment 2) and was amplified by the reporting of multiple features (Experiment 3). Taken together, these results suggest that selective internal attention induces competitive dynamics among features during visual learning, flexibly tuning object representations to align with prior mnemonic goals.

1. Introduction

Physical actions bring about lasting changes to objects we encounter. These interventions may be more consequential in some cases (e.g., transforming a forest into pulp) than others (e.g., thumbing through a new book), but totally inconsequential actions are rare. Just as physical objects bear traces of such encounters, mental objects may reflect their history of manipulation by the mind. This notion of 'cognitive actions' refers broadly to processes that manipulate mental representations in various ways. Understanding the consequences of such actions is especially important because they are the essence of human cognition (Andrews-Hanna, Reidler, Huang, & Buckner, 2010; Klinger & Cox, 1987; Mason et al., 2007; Singer, 1966). As a case study of cognitive actions, here we investigate the consequences of reflective, or internal attention (Chun, Golomb, & Turk-Browne, 2011; Chun & Johnson, 2011).

1.1. External and internal attention

Attention typically refers to the prioritization of sensory information that is either inherently salient (Theeuwes, 1992; Treisman & Gelade, 1980) or relevant to current goals (Most, Scholl, Clifford, & Simons, 2005). Deploying attention to certain information and not other information does not merely determine what gets processed downstream (Al-Aidroos, Said, & Turk-Browne, 2012), but can also alter the perceptual experience of this information (Carrasco, Ling, & Read, 2004). There are both benefits

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and costs of attention: processing of selected information can be facilitated (Posner, Snyder, & Davidson, 1980) and processing of unselected information can be inhibited (Houghton & Tipper, 1994).

These forms of attentional modulation can have longer-term consequences for memory. On the one hand, allocating attention to an item during encoding enhances its later recognition (Chun & Turk-Browne, 2007; Uncapher, Hutchinson, & Wagner, 2011). On the other hand, removing attention from an item during encoding not only worsens recognition, but can actually produce a memory cost for this item relative to novel items (Fox, 1995; Tipper, 1985). This cost may reflect an attentional weighting mechanism that actively inhibits distractors, shaping the representation of an item in memory based on current task goals (Lavie & Fox, 2000; Neill & Valdes, 1992).

The impact of attention on memory has been investigated mostly in the case of external attention, which entails the selection of representations that are directly supported by sensory information, and that do not require maintenance in working memory to remain active. Here we investigate the mnemonic consequences of *internal* attention, which we define as the selection of representations that are being maintained temporarily in working memory, and that are no longer supported by externally available sensory information. External attention might nevertheless provide a useful starting point for thinking about how internal attention affects memory. This analogy is supported by the fact that external and internal attention rely on similar mechanisms: (1) they are both highly selective and capacity limited (Chun et al., 2011), (2) deploying one form of attention interferes with the other (Awh & Jonides, 2001), and (3) both forms of attention engage overlapping networks of brain regions (Nobre et al., 2004).

1.2. Consequences of memory retrieval

Given these commonalities to external attention, memory may be enhanced when internal attention is allocated to an item and suppressed when it is removed from an item. Support for this prediction comes from research on retrieval from long-term memory. While overly simple conceptions of remembering liken retrieval to finding and reading a file from a hard drive, the act of recovering the contents of a representation from long-term memory actually alters these contents and affects subsequent retrieval of the same information.

These alterations can be beneficial. For example, testing of recently learned information—such as a history lesson (Nungester & Duchastel, 1982) or word pairs (Carpenter, Pashler, & Vul, 2006; Carrier & Pashler, 2002)—promotes long-term retention of this information. Moreover, retention is better after repeated testing (i.e., after multiple retrieval attempts) than after an equal number of opportunities to study the same material (Karpicke & Roediger, 2008; Roediger & Karpicke, 2006). Relatedly, information tends to be better remembered when it has been generated from internal knowledge than when acquired via external sources (Crutcher & Healy, 1989; Slamecka & Graf, 1978).

Memory retrieval can also have deleterious effects. For example, recall of one item from memory makes other related items less accessible for later recall (i.e., retrieval induced forgetting; (Anderson, Bjork, & Bjork, 1994, 2000). Specifically, in such studies, participants study a list of category-exemplar word pairs (e.g., Fruit-Grape, Fruit-Peach, Mammal-Cow), practice recalling a subset of the exemplars with a category cue (e.g., Fruit-G___?), and finally, perform a recollection test of all exemplars. Memory is better for the pairs practiced in the second phase (e.g., Fruit-Grape) relative to unpracticed pairs (e.g., Mammal-Cow), consistent with the testing effects described above. Among unpracticed pairs, however, memory is worse for those exemplars that share a category cue with a practiced exemplar (e.g., Fruit-Peach). These results are interpreted as evidence that inhibitory mechanisms suppress memory of competitors during initial recall.

1.3. Internal attention and visual learning

Previous work has focused on the retrieval of stable information from long-term memory, such as semantic categories and their members. However, similar competitive processes may operate in a short-term store of recently experienced visual information, when a subset of this information is selected via internal attention. This may help shape how items are represented during initial encoding, and ultimately guide longer-term learning about these items. This view is compatible with modal models of memory, which emphasize the importance of a short-term store as the nexus between ongoing perception and long-term knowledge (Shiffrin & Atkinson, 1969). Indeed, the hallmark of short-term memory is that representations can be manipulated in the service of ongoing behavior—including learning (Baddeley & Hitch, 1974).

Visual memory provides a fruitful domain in which to investigate the impact of internal attention on long-term learning. Specifically, what constitutes a unit of visual memory remains contentious (Fougnie, Asplund, & Marois, 2010), including theories based on: objects (Luck & Vogel, 1997), feature dimensions (Olson & Jiang, 2002; Wheeler & Treisman, 2002), and information load (Alvarez & Cavanagh, 2004; Bays & Husain, 2008; Brady, Konkle, & Alvarez, 2009). All of these theories share an assumption that the contents of memory are solely determined by properties of stimuli in the current display. However, we propose that the lack of consensus partly results from neglecting the role of prior experience in shaping how a given display or object is construed. In particular, beyond examining how prior perceptual experience affects visual memory (Brady et al., 2009; Curby, Glazek, & Gauthier, 2009), we consider how prior *retrieval* experience tunes object representations.

Initial insights can be gleaned from a version of the standard retrieval-induced forgetting task that used visual stimuli (Ciranni & Shimamura, 1999). Instead of relying on semantic associations between items, this study manipulated the perceptual similarity of items. Participants learned the location of twelve objects that were grouped by shape (e.g., circles, triangles, crosses) or color (e.g., green, orange, purple), practiced retrieving an associated