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To the Trained Eye: Perceptual Expertise Alters Visual Processing

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Abstract

Perceptual expertise refers to learning that is specific to a domain, that transfers to new items within the trained domain, and that leads to automatic processing in the sense that expertise effects can be measured across a variety of tasks. It can be argued that most of us possess some degree of perceptual expertise in a least one, if not several domains, thereby giving the study of perceptual expertise broad application. Some object categories may in fact be objects of perceptual expertise to the majority of people: Faces appear to be one such example. Thus, the use of face stimuli, or the comparison of face and object perception, can be a powerful way to ask whether a given process is influenced by perceptual expertise. Here, we emphasize one characteristic way that face processing appears to differ from nonface processing: that is, the degree to which they recruit a ''holistic'' rather than a ''featural'' perceptual strategy. This review brings evidence that expertise influences perceptual processing together with recent findings that the capacity of visual short-term memory is greater in perceptual experts and explores the relationship between the two.

Keywords: Perceptual expertise; Visual short-term memory; Face recognition; Object recognition

1. Introduction

We tend to conceive of experts as a select group of individuals whose command of a particular domain (e.g., X-rays, wine, birds) outshines that of the general population. *Perceptual expertise* refers to learning that is specific to a domain, that transfers to new items within the trained domain, and that leads to automatic processing in the sense that expertise effects can be measured across a variety of tasks (e.g., in passive tasks or under conditions

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where it would be more appropriate to use default novice strategies; Bukach, Gauthier, & Tarr, 2006). It can be argued that most of us possess some degree of perceptual expertise in a least one, if not several domains, thereby giving the study of perceptual expertise broad application. This review brings together evidence that expertise influences perceptual processing with recent findings that the capacity of visual short-term memory (VSTM) is greater in perceptual experts and explores the relationship between the two. What is the evidence that the changes in perceptual processing that accompany expertise may be responsible for effects of expertise on domain-general mechanisms like short-term memory? Can such findings help us understand the nature of these domain-general mechanisms?

Some object categories may in fact be objects of perceptual expertise to the majority of people: This appears to be the case with faces. Face perception is characterized by its extreme sensitivity to subtle changes in the spatial relations between features (Bruce, Doyle, Dench, & Burton, 1991; Haig, 1984; Hosie, Ellis, & Haig, 1988; Kemp, McManus, & Pigott, 1990). Adults can detect subtle changes in the configuration of facial features as small as 1 min of visual angle, which approaches the limits of normal visual acuity (Haig, 1984). Other work, summarized in this review, focuses more directly on the differences between face perception and typical object perception. The use of the face stimuli, or the comparison of face and object perception, is a powerful way to ask whether a given process is influenced by perceptual expertise (although this approach has stirred contention, e.g., McKone & Kanwisher, 2005). Here, we emphasize one characteristic way that face processing appears to differ from nonface processing: the degree to which they recruit a ''holistic'' rather than a ''featural'' perceptual strategy. We then review some studies exploring whether advantages in expert perception impact VSTM.

2. The holistic nature of face processing

Over the past few decades, it has been thought that faces are represented in two different ways, one of which is similar to how we represent objects, using features, and the other, unique to faces, using configural information such as the relationships between parts (Carey & Diamond, 1977; Yin, 1970). Studies manipulating the configural information in face stimuli have also led to the idea that faces are processed ''holistically.'' To some, this means that face representations themselves are holistic (Tanaka & Farah, 1993), with the information about the individual features (*featural information*) and the relations between features (*configural information)* being relatively inseparable (Farah, Wilson, Drain, & Tanaka, 1998; Tanaka & Sengco, 1997). To others, however, holistic effects do not necessarily reflect the format of the underlying representation and could have a more decisional basis (Wenger & Ingvalson, 2002). For instance, individual parts may be represented independently, but we may have learned through experience to attend to several of them at once and/or to consider evidence about one part when making decisions about another part. Few frameworks are suited to address the representational versus decisional locus of holistic processing, such that the locus of holistic processing is generally assumed according to theoretical preferences. Work that directly addresses this question tends to find a surprisingly strong decisional contribution (Richler, Gauthier, Wenger, & Palmeri, 2008), even though holistic processing occurs very early in time (Richler, Mack, Gauthier, & Palmeri, in press; Rossion, Gauthier, Goffaux, Tarr, & Crommelinck, 2002).[1] But regardless of its locus, evidence of holistic processing of faces abounds, resulting in a number of hallmarks of face perception that distinguish it from the perception of other nonface object categories (Tanaka & Farah, 1993; Tanaka & Sengco, 1997; Young, Hellawell, & Hay, 1987).

One such hallmark of face processing is the obligatory influence of task-irrelevant features on face part judgments demonstrated in a part-matching task with chimeric faces (Gauthier, Curran, Curby, & Collins, 2003; Young et al., 1987). Specifically, individuals are less accurate and/or slower at identifying a part of a face when it is presented as part of a chimeric face made from halves of different people's faces that are aligned together, relative to when the face parts are misaligned (composite effect; Young et al., 1987). This provides evidence of the difficulty observers experience when trying to process different parts of a configurally intact (i.e., aligned halves) face independently. Consistent with the absence of other hallmarks of face perception when faces are inverted (i.e., turned upside-down; Tanaka & Farah, 1993; Tanaka & Sengco, 1997), alignment has no effect on judgments about inverted chimeric face halves (Young et al., 1987). Although inversion may not completely abolish differences in processing between faces and objects (Sekuler, Gaspar, Gold, & Bennett, 2004), inversion selectively reduces configural and holistic processing (Bartlett & Searcy, 1993; Bruce et al., 1991; Collishaw & Hole, 2002; Kemp et al., 1990; Leder & Bruce, 1998, 2000; Leder, Candrian, Huber, & Bruce, 2001; Murray, Yong, & Rhodes, 2000; Rhodes, Brake, & Atkinson, 1993; Searcy & Bartlett, 1996; Tanaka & Sengco, 1997; Thompson, 1980). For example, observers are far more sensitive to configural changes in upright faces than in inverted or nonface objects, but inversion does not influence the ability to detect featural changes (Tanaka & Sengco, 1997). Thus, inversion disproportionately impairs observers' sensitivity to the configural information within faces, which appears to be a crucial element for the establishment of holistic face representations.

3. Face processing as a model of perceptual expertise

Some suggest that face processing is modular, supported by processes that overlap little with those used to perceive other classes of stimuli (Kanwisher, 2000; Kanwisher, McDermott, & Chun, 1997; McKone & Kanwisher, 2005). Others have proposed that faces are not inherently special, but rather that they recruit holistic and configural processing as a result of our extensive domain-specific experience with them (Diamond & Carey, 1986). Support for this ''expertise'' account of the specialization of face processing comes from the demonstration of a greater inversion effect for judgments about dogs among dog experts and for cars among car experts, compared to novice observers (Curby, Glazek, & Gauthier, 2009; Diamond & Carey, 1986; but see Robbins & McKone, 2006 for a failure to replicate this effect among dog experts). Expertise with other nonface objects (e.g., fingerprints and computer generated novel objects) has also been associated with a face-like inversion effect on the earliest face-selective potential detected by event-related potentials (ERPs) (Busey &

Vanderkolk, 2005; Rossion et al., 2002). Thus, extensive experience appears to contribute, at least in part, to the characteristic nature of face processing, as the processing of nonface categories can share characteristics with that of faces after extensive experience.

In addition to the inversion effect, more direct measures of holistic processing, such as the composite effect, have been obtained as a result of training observers to individuate nonface objects (Gauthier & Tarr, 2002; Wong, Palmeri, & Gauthier, 2009). For example, real-world car experts, relative to car novices, also have more difficulty processing only a part of a car when it is presented in the context of a whole car relative to car novices (Gauthier et al., 2003). In addition, several studies have shown that the robustly face-selective fusiform face area (FFA) in the temporal lobe, believed to be a critical node in the system responsible for face perception (Kanwisher et al., 1997), can be recruited by the perception of objects from a category for which expertise at individuating exemplars has been acquired (Gauthier, Skudlarski, Gore, & Anderson, 2000; Gauthier, Tarr, Anderson, Skudlarski, & Gore, 1999; Xu, 2005). This fusiform activity for objects of expertise correlates with the degree of behaviorally indexed holistic processing acquired by individuals in training studies (Gauthier & Tarr, 2002; A. C.-N. Wong, unpublished data). These and other results suggest that the acquisition of visual expertise with a particular category can result in a shift toward the recruitment of a cognitive processing strategy and neural substrate similar to those involved in face processing. Note, however, that not all kinds of visual expertise with objects recruit face-like strategies and neural systems. To the extent that other types of expertise involve perceptual problems other than individuation of visually similar objects, the systems involved are likely to be quite different. Recent work suggests that the processing strategies and neural substrates recruited by expertise can be influenced by the tasks used to train observers, rather than been wholly determined by the shape of objects (Wong et al., 2009, A. C.-N. Wong, unpublished data). Consistent with this idea, other types of expertise, for example, individuating letters or Chinese characters, or learning to read musical notation, engage networks of visual and nonvisual areas distinct from those associated with face perception (Schlaggar & McCandliss, 2007; Wong & Gauthier, in press).

Although the type of training may influence the processing strategy and neural substrates recruited, the specific category exemplars encountered during training likely play a role in shaping the boundaries of an individual's domain of expertise. For example, expertise with modern cars, and the associated holistic processing style adopted, does not transfer to antique cars (Phillips, Grovola, Bukach, & Gauthier, 2007). Similarly, recognition of faces from an unfamiliar race is impaired and such faces are processed less holistically than are own-race faces (Tanaka, Kiefer, & Bukach, 2004). However, previous studies (that did not manipulate race) have shown an inversion effect with both familiar and unfamiliar faces (Scapinello & Yarmey, 1970; Yarmey, 1971). In addition, modern car experts demonstrate holistic processing of novel cars made from the tops and bottoms of different modern cars (Gauthier et al., 2003). Thus, perceptual expertise effects do not depend on familiarity with an exemplar, but even within the trained domain, generalization is limited to objects that are relatively close to trained exemplars in similarity space.

The work described above cannot distinguish whether the processing mechanisms supporting face and nonface expert processing are just similar, but functionally independent, or whether they truly depend on common resources. But other studies provide more direct evidence of a functional overlap between face and nonface object expertise by demonstrating interference between face and car processing in car experts (Curby & Gauthier, 2001; Gauthier et al., 2003; Rossion, Collins, Goffaux, & Curran, 2007). The level of interference measured between the processing of these categories depended on the degree to which the car task recruited a holistic processing strategy (Gauthier et al., 2003). More specifically, this level of interference depended both on one's visual expertise with cars and on whether the cars were configurally intact, as both these factors modulate holistic processing. In an interleaved two-back task that depends on VSTM, observers were asked to hold part of a car stimulus in memory while processing part of a face. The degree of holistic processing of the cars was manipulated by inverting the part of the car that was irrelevant. When cars were in the normal configuration, holistic processing naturally varied as a function of participants' perceptual expertise with cars. Car experts processed faces in the context of normally configured cars less holistically than faces processed in the context of cars in a modified configuration (tops inverted). Importantly, cars in a modified configuration were processed less holistically, and therefore presumably competed less for holistic processing resources. Interestingly, this competition was reflected in the magnitude of the face-selective N170 potential in response to faces, which decreased in the context of the nonmodified cars. Functional overlap between face and expert object processing was also demonstrated in lab-trained experts (Rossion, Kung, & Tarr, 2004) in a study where participants attended to a centrally presented novel object (greeble) and reported on which side of the screen a distractor face appeared. After expertise training with greebles, the N170 in response to the distractor face was reduced when participants were concurrently attending a greeble compared to a novel (untrained) object. These studies suggest that the concurrent processing of nonface objects from a domain of expertise interferes with early face-selective responses. Some evidence suggests that the locus of such interference may be perceptual rather than in VSTM. A very brief temporal interval (200 ms) separating a face and object of expertise reduces the degree of interference obtained by task-irrelevant objects (Rossion et al., 2007). Furthermore, cars held in VSTM during a face composite task, with a 400-ms mask separating stimuli of each domain, do not reduce holistic processing of the faces, even in car experts (Cheung & Gauthier, in press). One interpretation of such results is that the effect of perceptual expertise is observed on perceptual tasks but is irrelevant to the functions of domain-general mechanisms such as VSTM. However, recent research suggests that expertise can influence how much information can be stored in VSTM.

4. Benefits of perceptual expertise: A VSTM advantage for objects of expertise

Visual short-term memory refers to the limited capacity mechanism(s) responsible for the temporary representation and maintenance of visual information in the absence of external input. Thus, VSTM is akin to the passive visual cache proposed as an extension to Baddeley's classic multicomponent model of working memory (Baddeley & Hitch, 1974; Logie, 1995). The capacity of VSTM, although varying across individuals, has been assumed to be fixed within individuals and thus immune to the effects of experience (Luck & Vogel, 1997; Vogel & Machizawa, 2004). However, if expertise leads experts to use different strategies and to perceive objects more efficiently, does that provide some advantage to experts regarding how much information can be stored in VSTM? The answer would provide valuable insight not only into the effects of perceptual learning on visual processing, but also into the nature of the mechanisms determining the capacity of VSTM.

The capacity of VSTM can be influenced by factors such as perceptual organization of the items to be encoded. For example, whether visual features are attributed to the same or different objects impacts VSTM capacity for these features; although observers can only reliably retain information about four colors or four line orientations, they can retain information about four *objects* defined by conjunctions of up to four different features, thereby allowing observers to retain 16 features providing they are only distributed across four objects (Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001). This has led some to suggest that VSTM capacity is governed by a fixed object-based limit (Luck & Vogel, 1997). Others have provided evidence that although VSTM capacity for objects consisting of a number of simple features can appear to be strongly object-based, VSTM for complex stimuli does not fit with a strong object-based account (Alvarez & Cavanagh, 2004; Olson & Jiang, 2002). For example, contrary to a strong object-based account, VSTM capacity for object categories that vary in complexity, from simple colored squares to complex line drawings of familiar objects, is highly correlated with the information load for each category (Alvarez & Cavanagh, 2004), where information load was defined as the rate at which items of a particular category could be searched for a target.[2] Thus, VSTM capacity is at least partly determined by the nature of the items being stored, with more complex objects requiring more ''space'' in VSTM.

Visual short-term memory is influenced not only by the organization of features into objects but also by the organization and types of features *within* objects. For example, VSTM for multiple features is improved when the features come from the same part, compared to different parts, of an object (Xu, 2002). In addition, Wheeler and Treisman (2002) found evidence suggesting that features from the same dimension (e.g., color) compete for capacity, whereas features from different dimensions (e.g., color and orientation) can be stored in parallel (Delvenne & Bruyer, 2004; Wheeler & Treisman, 2002). Notably, they suggest that VSTM is limited not only by the capacity of dimension-specific feature stores but also by the binding of object features using attentional resources that also have limited capacity. Features such as shape and texture can be bound together in VSTM and stored just as well as a single feature, providing that the features share the same coherent boundary and thus share the same spatial location (e.g., a textured square; Delvenne & Bruyer, 2004). Thus, object-based hierarchical feature coding appears to influence VSTM capacity, suggesting that the perceptual organization and types of features present within objects may also have consequences for VSTM.

Most studies looking at VSTM capacity have focused on the influence of task- and stimulus-based factors, such as object structure or complexity without addressing how learning or experience might impact VSTM. VSTM capacity estimates of three to four items remain stable from early in development (12 months; Rose, Feldman, & Jankowski, 2001) to adulthood (Luck & Vogel, 1997), suggesting that VSTM capacity may be relatively inflexible and immune to the effects of learning. However, one line of research, looking at expert chess players, suggests that task-specific experience and training can have a profound impact on short-term memory (Chase & Ericsson, 1981). Chess experts have a better memory for chess piece configurations, especially ''legal'' ones, apparently due to ''chunking'' of information into meaningful units in long-term memory, allowing experts to store pointers to these chunks in VSTM (Chase & Simon, 1973; Freyhof, Gruber, & Ziegler, 1992; Gobet & Simon, 1998). These chunks can be used as a processing unit, and—importantly—can be retrieved by a single act of recognition (Gobet & Simon, 1998). Therefore, because the apparent increase in VSTM found in chess experts is thought to stem from the recruitment of additional, *long-term memory* resources, it is unclear what this says about the role of experience on VSTM capacity itself.

A small number of studies address this question and have found limited effects of familiarity with the objects used in a VSTM task. For instance, familiarity with specific shapes (novel polygons) acquired through a single session of practice in a VSTM task does not lead to an increase in capacity relative to novel shapes (Chen, Eng, & Jiang, 2006; see also Olson & Jiang, 2004). However, our own work suggests that more extensive experience, such as that required to develop perceptual expertise at individuating objects from a real-world category, can increase VSTM performance (Curby & Gauthier, 2007; Curby et al., 2009). First, despite their complexity,[3] that would be expected to considerably reduce capacity (Alvarez & Cavanagh, 2004), we found that VSTM capacity for upright faces was in the range of that reported for very simple objects, such as simple colored circles (i.e., three to four items). When faces are presented in an inverted orientation, such that observers can no longer benefit from their extensive experience, VSTM dropped to the level expected on the basis of the perceptual complexity of face stimuli. Thus, one consequence of expertise appears to be the reduction of the impact of perceptual complexity on VSTM capacity, allowing VSTM to approach that of simpler items.

Consistent with the proposed role of perceptual expertise in reducing the impact of perceptual complexity on VSTM capacity, we also found that car experts show a similar VSTM advantage for cars, but only when cars were presented in the familiar upright orientation (Fig. 1; Curby et al., 2009). As in previous studies using real-world car experts (e.g., Gauthier et al., 2000), participants' expertise was quantified using a sequential same/different judgment with cars (at the level of model regardless of year, e.g., Honda Accord 1995 and a Honda Accord 1999 would appear in a ''same'' trial). The degree of participants' car expertise was then found to be correlated with participants' VSTM for upright, but not inverted, cars. Previous studies have shown that car expertise measured in this manner correlates with other markers of perceptual expertise, including FFA activation, the amplitude of the N170 potential, and sensitivity to changes in the spatial frequency content of images (Gauthier, Curby, Skudlarski, & Epstein, 2005; Gauthier et al., 2000, 2003; Rossion et al., 2007; Williams Willenbockel & Gauthier, in press). Therefore, extensive experience with a category can result in a domain-specific increase in VSTM performance for complex objects, perhaps because experts can more efficiently encode and represent complex objects in VSTM.

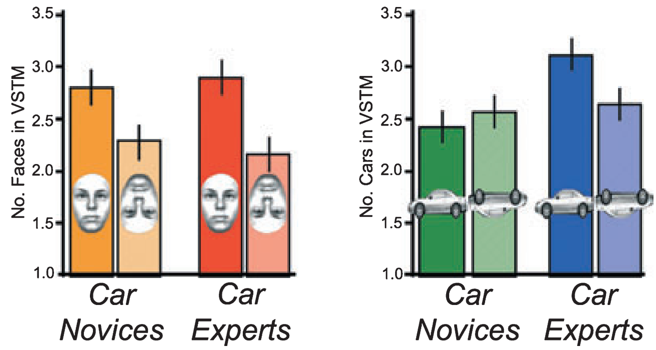

Fig. 1. The maximum number of face (left) or cars (right) in visual short-term memory (VSTM) for upright and inverted faces and upright and inverted cars among participants who were car experts and car novices from Curby et al. (2009). There was a VSTM advantage for upright cars among car experts similar in magnitude to the advantage for upright faces. Car experts, but not novices, showed an inversion effect for cars.

Notably, this VSTM advantage cannot be explained by the presumably greater availability of verbal labels for cars among car experts relative to those available to car novices: The VSTM advantage remained even after a simultaneous articulatory suppression task was increase from two digits to three car model names (Curby et al., 2009). The use of car model names (whose corresponding image was not present in the visual set) was used to introduce semantic interference and would thus greatly impair performance if a verbal strategy were to be used. In addition, the failure of stimulus familiarity to impact the VSTM advantage for upright over inverted faces provides further evidence against a contribution of a naming strategy to the expert VSTM advantage: VSTM for famous faces showed the same orientation-specific VSTM advantage as unfamiliar faces (Curby et al., 2009).

What is the underlying mechanism behind perceptual experts' VSTM advantage? The fact that the VSTM advantage for faces or cars in experts shows an inversion effect is consistent with the idea that holistic processing is responsible for the effect. But note that this represents relatively indirect evidence: Expertise is related both to VSTM capacity and to holistic processing, and both effects are reduced by inversion. Other findings suggest that, consistent with object-based theories of VSTM capacity, holistic encoding may allow experts to incorporate more features into the unified object representations suggested to serve as the units of VSTM (Scolari, Vogel, & Awh, 2008). This could be especially beneficial for discriminating between highly similar exemplars of complex objects such as cars. Therefore, holistic processing may allow experts to maximize the use of an inherently limited VSTM system. The impact of perceptual expertise on VSTM may stem from changes in the hierarchical organization of features within object representations. Specifically, holistic representations may lead to a tighter binding of features or the creation of larger featural units and thus fewer feature boundaries within representations of objects of expertise. Further insights into how perceptual expertise may benefit VSTM capacity are provided by Wheeler and Treisman's (2002) findings that VSTM appears to be limited by the requirement of capacity-limited attention to bind features together. It is possible that binding of features within objects of expertise is facilitated by holistic encoding processes, thus increasing VSTM performance by reducing the burden on capacity-limited attentional mechanisms.

A recent neuroimaging study explored the impact of extensive training on the neural substrates supporting VSTM (Moore, Cohen, & Ranganath, 2006). Training increased activity during both encoding and maintenance of artificial objects in the classic VSTM network, including the bilateral dorsolateral prefrontal, posterior parietal, and occipitotemporal cortices. In contrast, the lateral occipital cortex and the fusiform face area (FFA) showed expertise effects during encoding only. Although this supports the suggestion that VSTM is supported by the interaction of domain-specific neural representations with frontal and parietal regions, VSTM capacity was not measured in this study, so it is unclear whether increases in capacity in experts would correlate more with changes in encoding or maintenance and with posterior or anterior cortical areas.

Other studies provide insight into the possible locus of the expertise effect on VSTM capacity (Song & Jiang, 2006; Xu & Chun, 2006). Specifically, Xu and Chun (2006) found that although activity patterns in the inferior intraparietal sulcus (IPS) suggest that this node of the VSTM system has a fixed capacity of about four objects (regardless of object complexity), activity patterns in the superior IPS and the lateral occipital complex (LOC) suggest that the capacity of these areas is variable, depending on the complexity of the objects stored. Thus, the complexity induced bottleneck in the superior IPS and LOC appears to underlie the lower VSTM capacity for complex objects. Thus, if the constraints on VSTM associated with object complexity can be localized to the LOC, an object form processing area, the expert VSTM effect may stem from the FFA, which is implicated in expert object form processing (Gauthier et al., 1999, 2000, 2005; Xu, 2005). Consistent with this possibility, the FFA is engaged during VSTM task with faces (Druzgal & D'Esposito, 2001, 2003). In addition, FFA activity after lab-based expertise training is correlated with some measures of holistic processing (Gauthier et al., 1999). Thus, the recruitment of the FFA for objects of expertise and the resulting holistic processing strategy may allow experts to better encode complex visual information, potentially reducing the cost of complexity on VSTM performance. This would suggest that superior IPS and/or occipital/temporal activation reflects the perceived, rather than physical, complexity of objects in VSTM.

5. Conclusion

Evidence suggests that the change in cognitive strategy that comes with perceptual expertise has far-reaching consequences for visual cognition more generally. For example, the expertise-related holistic shift in processing strategy is a viable candidate to explain how perceptual expertise influences the capacity of VSTM. Findings such as these not only provide insight into the potential of perceptual training to alter performance but also provide insight into the nature of these higher-level visual functions themselves. Many questions remain, including whether holistic processing also contributes to domains of expertise where LTM is thought to be especially critical, such as chess, and whether individual differences in VSTM capacity end up influencing one's ability to acquire a holistic processing strategy through experience.

Notes

1. Note than an ''early'' effect does not effectively rule out the contribution of response bias, which can in principle impact any decision performed at any level within or by an organism.
2. Measuring the visual complexity or information load of stimuli, especially real-world stimuli such as faces or scenes, is a topic of much interest and it has a long history in the field of visual cognition (see Donderi, 2006 for an insightful review).
3. Eng, Chen, and Jiang (2005) reported that the information load was higher for faces than for any other stimulus category tested (cubes, squiggles, polygons, letters, and colored patches).

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