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Benefits and costs of uniqueness in multiple object tracking: The role of object complexity

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ABSTRACT

How do unique objects affect multiple-object tracking? Recent research has catalogued seemingly contradictory findings, varying from enhanced to impaired tracking performance. In this study, we explore the role of object complexity in this broad range of phenomena. In a series of three experiments, we demonstrate that unique objects of varying complexity can produce both costs and benefits on tracking performance. These experiments show that the key effects of uniqueness in object tracking are results of a tradeoff between tracking operation and processing of object identity information within the capacity limit of working memory.

1. Introduction

The multiple-object tracking (MOT) paradigm has been widely used as a tool for studying attention and visual cognition (Scholl, 2009). Although most MOT tasks have employed identical objects as tracking stimuli, there is now a growing interest in visual tracking of unique objects (Horowitz et al., 2007; Makovski & Jiang, 2009a, 2009b, Ren et al., 2009). As most authors are well aware, accurate identity-location binding serves meaningful functions in many real-world tracking tasks. For example, a living organism has to identify which moving objects pose a potential danger; a basketball point guard has to be aware of where every teammate and opponent is in order to make a successful pass, etc. Given the ecological significance of object features for identity tracking, it seems rather unlikely that people would ignore this information in multiple object tracking. Intuitively, individuating objects should benefit tracking performance of MOT, because by remembering object identities at the target tagging phase, observers should be able to recover the lost targets during tracking. In other words, we may find "where" an object is by knowing "what" it is. However, one of the surprising conclusions from prior MOT research is that identity processing of the objects differentiated by features appears to be rather detached from tracking. For example, there is evidence that individuating objects by color does not help tracking performance (Klieger, Horowitz, & Wolfe, 2004). Moreover, people are often quite poor at recalling the identity of correctly tracked objects (Pylyshyn, 2004), or noticing when target properties change (Bahrami, 2003). These findings suggest that tracking is accomplished entirely by updating an object's spatiotemporal information, and that the identity of the object is largely ignored during this operation. Pylyshyn's (1989, 2001, 2004) model, Fingers of INSTantiation (FINST), was created to accommodate this line of findings. According to FINST, MOT is implemented by early vision that picks out a small number of objects while ignoring their visual properties. This early vision is "feature-blind" because the object identity differentiated by visual properties is not encoded or accessible for higher level cognitive processes.

However, recent evidence has revealed that observers can actually take advantage of the additional information provided by unique objects. Tracking performance can benefit from distinct shapes, numbers or colors (Horowitz et al., 2007; Makovski & Jiang, 2009a, 2009b). Makovski and Jiang (2009b) suggest that target identities are actively maintained in working memory. This idea is consistent with object file theory (Kahneman, Treisman, & Gibbs, 1992), according to which, featural properties, along with other semantic information of the objects, are encoded and updated across time and space. Kahneman et al. tested the theory in a reviewing paradigm, which involved briefly labeling two objects with unique letters (e.g., 'A' and 'B'). After the two objects moved smoothly to different locations, they asked observers to name the letter that appeared in one of the two objects as quickly as possible. Observers were faster when the letters reappeared at their original objects. They called this 'the object-specific benefit'. Other researchers who have found an advantage of unique objects have also pointed out the connection between their finding and the

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object-specific benefit (Horowitz et al., 2007; Makovski & Jiang, 2009b). They argue that object files are content addressable and that the visual system can take advantage of the differences between unique objects stored in working memory to optimize tracking performance.

However, identity processing in MOT does not always benefit tracking. Botterill, Allen, and McGeorge (2011) found that processing identity information (or features) has no effect on tracking performance. Moreover, if human faces are used as tracking stimuli, unique identities could even impair tracking performance (Ren et al., 2009). Recent research into unique object tracking has thus generated a set of rather bewildering results. How can unique objects be a benefit in one study yet a deficit in another? Why do unique objects produce significant effects in some conditions yet null results in others? What underlies this wide range of seemingly contradictory findings? Do they reflect reality or emerge as a result of varying experimental procedures? In this study, we aim to show that these phenomena are necessary consequences of identity processing. It is this processing activity that underlies the intricate tradeoff between the benefits and costs of unique object tracking. Our proposal relies on two assumptions. The first is that identity processing in MOT must share the limited attentional resources with tracking operation. The second is that the efficiency of identity processing is affected by object complexity. Using the same set of stimuli and experimental procedures, we hope to demonstrate that the manipulation of object complexity can produce a diverse pattern of effects that reflect the nature of tradeoff in unique object tracking without suffering the difficulties that often confront comparisons of different studies.

Following Ren et al. (2009), our predictions about these diverse effects rely on the assumption that resources are shared by identity processing and tracking. Cohen et al. (2011) have recently contrasted this common-resource model with the model that assumes separate resources for identity processing and location tracking (Botterill, Allen, & McGeorge, 2011; Horowitz et al., 2007). Their experiments have produced evidence for the common-resource model.

It has been shown that unique objects can enhance tracking performance by recovering lost targets (Horowitz et al., 2007; Makovski & Jiang, 2009b). However, because identity information is encoded and stored in visual working memory, this process is attentionally demanding (Fougnie & Marois, 2006; Makovski & Jiang, 2009b). Makovski and Jiang (2009b) found that unique objects can benefit tracking when concurrent working memory load is low, but the effect can be largely eliminated when concurrent working memory load is high. This suggests that the efficiency of identity processing depends on working memory load.

The efficiency is also affected by the characteristics of tracked objects, particularly by object complexity (Alvarez & Cavanagh, 2004). Recent research has suggested that the capacity of visual working memory is inversely related to object complexity: the more complex the stimuli, the lower the capacity (Alvarez & Cavanagh, 2004; Luria et al., 2010). Alvarez and Cavanagh (2004) measured the capacity for several object categories of varying levels of complexity indexed by information load, which reflects the efficiency of object processing. The results showed a decreased capacity as a function of object complexity (e.g., 4.4 for simple colors, 2.8 for Chinese characters), and suggested that the processing of complex stimuli requires more resource than simple stimuli. These results have important implications for MOT because the task requires visual working memory (Allen et al., 2006). Like the working memory tasks, complex objects in MOT should require more resources to process identity information.

Complex objects may also cause a higher degree of confusion between targets and distractors because they tend to be more difficult to discriminate from each other. This is quite likely because simple objects are usually distinguished by simple features whereas complex objects are distinguished by combined features. Thus, it is likely that identity processing may compete with tracking for more resource when objects are more complex. Because identity processing shares the resources used by tracking, this competition could in turn cancel the benefit of target recovery by object identities, or even lead to a reversed effect. This may explain the cost of uniqueness in Ren et al. (2009), where human faces were used as tracking stimuli. Faces are more complex than colors and simple shapes (Eng, Chen, & Jiang, 2005).

However, this hypothesis still requires evidence from other object categories. Although identity processing in multiple face tracking produced a tracking deficit (Ren et al., 2009), it is unclear whether the deficit is generalizable to non-face stimuli. Because face identities are especially important for social interaction, it is possible that they activate a greater level of identity processing than non-face stimuli. However, this cannot rule out the possibility that other complex objects also impair tracking. Furthermore, variations in object category and experimental procedure may be responsible for the different tracking effects reported in different studies. To tackle these issues, we employed numbers and Chinese characters as our tracking stimuli in this study. The visual complexity of these non-face objects was manipulated to investigate how it affects identity processing and tracking operation.

Various measures of stimulus complexity such as "figure goodness" (Garner & Sutliff, 1974), "perimetric complexity" (Attneave & Arnoult, 1956; Pelli et al., 2006), as well as "informational load" (Alvarez & Cavanagh, 2004), have been proposed. We employed the perimetric complexity, which is a widely-used index in the study of letter and character recognition. This measure is defined as the square of the inside and outside perimeter of a symbol, divided by the "ink" area (Pelli et al., 2006). The index of perimetric complexity correlates well with figure goodness, which corresponds well with the index of informational load (see Jiang, Shim, & Makovski, 2008).

It is unclear how objects with different levels of complexity create various attentional loads on the tracking operation. Makovski and Jiang (2009b) proposed that attentional load is evoked by a voluntary strategy to actively encode and store identity information in working memory. According to this hypothesis, observers only attend to identity information when it is beneficial. This account is able to explain some existing data quite well. For example, if targets in a MOT task periodically change to different identities, observers would not be able to rely on object identities to recover lost targets. Makovski and Jiang reasoned that because identity processing is useless in this condition, observers would abandon the use of object identity as their strategy. Hence they predicted a diminished benefit of unique objects. This was exactly what they found. Their account can therefore explain results that either showed a benefit or a null effect of unique object tracking.

However, this account would have difficulty in predicting deficit in tracking of unique complex objects. It could be inferred from the strategic identity processing view that ambiguous or overcomplex identities will not be processed during MOT because they bring no benefit (e.g., objects distinguished by conjunction of features such as color and shape). However, complex objects should not produce a cost to tracking if identity processing could be abandoned easily when the strategy is no longer useful. Thus, it is possible that identity processing is not completely voluntary. This will make it possible to anticipate a cost to tracking when object identities are unduly complex. According to this hypothesis, identity processing is likely to be performed by default. It is sometimes involuntary rather than being always dictated by a conscious decision. Hence, even when this activity is detrimental to tracking, the system would not have an easy procedure to halt the process. We should point out that Ren et al. (2009) have previously used the