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Commentary

Top–down contingent attentional capture during feed-forward visual processing

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Theeuwes (2010) summarizes an impressive number of studies demonstrating interference by irrelevant visual singletons in computer experiments with humans. In these studies, if participants search for a relevant singleton target, such as the single diamond among circles (i.e., a shape singleton), an irrelevant singleton distractor, such as the single red circle among the green stimuli (i.e., a color singleton), delays the correct response to the target (cf. Theeuwes, 1991, 1992). If this distractor – as was the case in the relevant experiments – does not predict the likely target position, it is said to be irrelevant. Theeuwes (2010) argues that the interference by the irrelevant distractor reflects stimulus-driven or exogenous capture of attention by singletons or feature contrasts, which he assumes to occur early during the feed-forward phase of visual processing.

According to this explanation, a stimulus initially captures attention exogenously (i.e., in a stimulus-driven way) to its position, to the degree to which it is salient. Salience in turn is defined as the summed local contrast in terms of color, luminance, and orientation difference to the surrounding stimuli or the background (cf. Bergen & Julesz, 1983; Itti & Koch, 2001). Theeuwes (2010) assumes that this salience-driven capture of attention is fast and occurs within 150 ms since singleton onset, during the feed-forward phase of visual processing (cf. Lamme, 2003).

In contrast to Theeuwes (2010), we think that top–down contingent capture is the rule and explains initial and fast attention capture effects in the first feed-forward phase of visual processing. During a later phase and under some conditions exogenous capture of attention possibly follows. At the same time, we propose that the evidence presented by Theeuwes fails to support exogenous orienting because it fails to exclude a top–down contingent capture explanation. We present our arguments in two sections. First, we review the evidence directly supporting our claim that salience capture is subject to top–down control. From this evidence we derive the *exogenous-capture criterion* that must be met by experiments for demonstrating exogenous spatial attention, and show that this criterion in not met by the studies reviewed by Theeuwes. Second, we review studies showing attentional capture by stimuli during the feed-forward phase, and conclude that only top–down contingent capture but no exogenous-capture can be observed during the feed-forward phase of visual processing.

1. The exogenous-capture criterion

A number of visual search studies demonstrated that participants exert top–down control over attentional capture (reviewed recently by Burnham, 2007). In the corresponding studies, the experimenter secures the participant's top–down control over attention by declaring a specific visual feature as defining the target, or at least as being informative for finding the target. The amount of attentional capture can then be compared under two conditions: with stimulus features (or feature contrasts) that match the search templates of the participants (i.e., their top–down control settings for attentional capture) and with stimulus features (or feature contrasts) that do not match the top–down control settings. In these studies, researchers inferred top–down control over attentional capture from stronger or even exclusive attentional capture by stimuli with matching features or feature contrasts (cf. Bacon & Egeth, 1994; Folk, Remington, & Johnston, 1992).

Folk et al. (1992), for instance, presented irrelevant red distractors prior to red targets in some of their blocks, and prior to white targets in other blocks. These distractors were irrelevant because they were not informative about the likely target location. Top–down controlled attentional capture was demonstrated in that study: The red distractors captured the participants' attention if they searched for the red color targets but not if they searched for the white targets. This finding was replicated many times and in different laboratories (e.g., Ansorge & Heumann, 2003; Eimer & Kiss, 2008; Folk & Remington, 1998).

The finding that attentional capture depends on the match between the attentional control settings and features of the attention-capturing stimulus has implications for proofs of exogenous attention, too. That is, from these studies follows that demonstrating exogenous or stimulus-driven attentional capture requires that no relevant task set to search for the attention-capturing feature or feature contrast of a distractor stimulus exists (cf. Bacon & Egeth, 1994; Folk et al., 1992). This is the exogenous-capture criterion.

Importantly, the exogenous-capture criterion is not met by the studies that have been reviewed by Theeuwes (2010). This is because all of Theeuwes' reviewed studies used singletons – a stimulus which is salient on a particular dimension – as the relevant

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targets and as the irrelevant distractors. Thus, if participants searched for the target by looking for a singleton – that is by using a top–down controlled singleton-detection mode – attentional capture would not be exogenous, but instead endogenously controlled by top–down attentional set (Bacon & Egeth, 1994; Leber & Egeth, 2006). By implication, an experimental set up that allows singleton-detection mode to find the targets is inadequate to assess the exogenous attentional capture by a salient stimulus.

To recapitulate the well-known key finding, Bacon and Egeth (1994) confirmed that participants can exert top–down control over feature singleton search (or search for feature contrasts). Bacon and Egeth's participants had to either search for a shape singleton (i.e., the one square-shaped target among circular distractors) or for a shape feature (i.e., the square-shaped target among circular, triangular, and diamond-shaped distractors). These authors found that participants oriented towards color singletons (i.e., the one red stimulus among green stimuli) if they searched for shape singletons but not if they searched for a specific target shape. As it is the case with top–down control settings for particular features (e.g., colors; cf. Folk et al., 1992) participants' attention was thus solely captured by feature singletons (or feature contrasts) if the participants actively searched for feature singletons in a top–down controlled manner.

This form of top–down control over attentional capture (i.e., singleton-detection mode) was possible in all studies that Theeuwes (2010) reviewed (e.g., Belopolsky, Schreij, & Theeuwes, 2010; Hickey, McDonald, & Theeuwes, 2006; Maljkovic & Nakayama, 1994; Ogawa & Komatsu, 2004; Schreij, Owens, & Theeuwes, 2008). For instance, Belopolsky et al. (2010) reported that their participants' attention was captured by uninformative singleton distractors when searching for singleton targets in (an adapted form of) Folk et al.'s (1992) paradigm. True, this finding is at odds with that of Folk et al., in that the exact feature of the distractor did not modulate attentional capture by the distractor; yet this result does not necessarily demonstrate exogenous attentional capture. Participants could well have searched for all targets as singletons in a top–down controlled manner.

The study by Schreij et al. (2008) provides an equally equivocal example. In that study, participants again had to search for a singleton in a version of Folk et al.'s (1992) paradigm. Schreij et al. (2008) found that adding one placeholder element (a frame) in the target displays of Folk et al. (1992) increased search times. (Note: the added frame appeared simultaneously with the target, preceded by a matching or non-matching distractor as a cue). It is tempting to exclude Schreij et al. (2008) from the present discussion of the possibility of attentional capture by salient stimuli, because this experiment involves a sudden onset as the capturing feature, which might be a special property apart from and above of being the only salient change in the display. But for the sake of simplicity, let us assume for the moment that being the only onset in a display is just another dimension on which the singleton can be different from the remainder of the display. However, if this is assumed, the exogenous onset criterion is again not met: The onset singleton captures attention while participants are searching for a color singleton.

We might note several other features which are problematic with this study. First, Schreij et al. (2008) regard the additional frame as a distractor which is to be ignored. Given that the additional frame was similar to that surrounding the potential target, it is not clear that participants treated the frame as an irrelevant feature; rather because of the similarity of the additional frame with the target-surrounding frame the additional frame might well be processed as an additional potential target location. After all, an increase of search times by the addition of a target-similar distractor to a search display is a standard finding in the visual search literature (cf. Duncan & Humphreys, 1989; Treisman & Gelade, 1980; Wolfe, 1994).

It is certainly noteworthy that the additional placeholder increased search time even though the participants' attention was captured by a matching distractor presented in advance of the target display. Thus, one might wonder whether the capture effect of the target-preceding distractor should not have bailed out any potential capture effect of the additional placeholder element in the target display. This line of thinking, however, presupposes that the top–down matching cue captured attention in a deterministic manner, in all trials, and to a maximal extent, which has never been claimed or shown. In addition, attentional capture by the top–down matching color distractor preceding the target display in Folk et al. (1992) and in Schreij et al. is brought about by color, whereas attentional capture by the additional placeholder element in the target display of Schreij et al. is brought about by shape. Because the features were different, both features could have captured attention in a top–down controlled fashion but independently of one another. Additive capture effects by two features are equivocal with respect to their origin as top–down contingent or exogenous as long as both match the set of searched for target features. To conclude, the exogenous-capture criterion was not met by any of the studies that Theeuwes (2010) reviewed.

2. Attentional capture during the feed-forward phase of visual processing

Theeuwes (2010) took precautions against this counter argument by using one additional criterion for exogenous attentional capture: its swiftness. Theeuwes declared that salience-driven capture occurs during an early feed-forward phase of visual processing. He estimates the duration of this phase of visual feed-forward processing to be 150 ms. This duration is a little longer than the 100 ms that have been estimated as the duration of the visual feed-forward processing phase in the physiological literature (cf. Lamme, 2003; Lamme & Roelfsema, 2000). The numerical difference may be due to differences in measurement: while Theeuwes bases his estimate on behavioral observations (cf. Donk & van Zoest, 2008), Lamme and colleagues base their estimate on cell recordings.

Theeuwes (2010) argues that if a singleton captures attention during the first 150 ms (the duration of the feed-forward phase), the capture effect can safely be attributed to stimulus-driven processes (e.g., Ogawa & Komatsu, 2004). Moreover, he uses this speed assumption also to dismiss counter evidence from studies confirming top–down controlled singleton capture or top–down controlled capture by feature disctractors. With respect to top–down controlled singleton capture (Leber & Egeth, 2006), Theeuwes observed that RT increased in the singleton-detection mode. With respect to top–down controlled capture by feature distractors (Folk et al., 1992), he argues that if the distractor–target intervals exceeded zero, an alternative interpretation of the intentional modulation of attentional capture is possible: In these studies, similar initial capture by matching and non-matching singleton distractors during the feed-forward phase of processing could have given way to a quicker deallocation of attention from non-matching than matching singleton distractors thereafter. As a consequence, only attentional capture by the matching singleton distractor would be observed.

We do not object to the theoretical possibility of the deallocation explanation; however, we object to Theeuwes' inconsistent use of the speed assumption and against his selective review of the corresponding evidence. Firstly, Theeuwes uses the speed assumption to explain findings that have been interpreted in favor of top–down control over attentional capture by Folk et al. (1992). On this argument, the relatively long interval between distractor and target makes it difficult to unequivocally track the origin of the capture effect to the feed-forward phase. This criticism, however, equally disqualifies findings like those of Belopolsky et al. (2010), which used the same timing as Folk et al. These studies are equally equivocal with respect to the particular point in time at which the irrelevant singleton captured attention. If Theeuwes' argument holds, in these studies, the irrelevant singleton might have captured attention very early after distractor onset, but maybe singleton capture occurred also later at any other point in time during the interval between singleton and target.

The same argument holds for inter-trial priming studies. Theeuwes (2010) reviews a number of studies in which attentional capture by a particular feature singleton in trial *n* facilitates attentional capture by a similar feature singleton in a subsequent trial $n+1$. This facilitation of singleton search is found in comparison to conditions with a different feature singleton in trial $n+1$ than trial *n* (Hodsoll, Mevorach, & Humphreys, 2009; Kumada, 1999; Maljkovic & Nakayama, 1994). The typical inter-trial interval in these studies is at least 1000 ms. On the basis of the length of the inter-trial interval alone, inter-trial priming of singleton capture cannot demonstrate singleton-driven capture during the feed-forward phase of processing.

In addition, there are further reasons that make inter-trial priming effects a complicated argument for Theeuwes' (2010) salience-driven attentional capture concept. First, during inter-trial priming of singleton capture, singleton *features* in trial *n* influence *singleton capture* in trial $n+1$. This indicates that singleton capture in trial $n+1$ cannot be safely tracked to the strength of the visual feature contrast in trial $n+1$ alone. This is in direct contradiction to Theeuwes' assumption of a bottom–up effect of salience on attentional capture. Second, it maybe also of interest to the reader that it is fiercely debated whether inter-trial priming of singleton capture is indeed a stimulus-driven effect, as Theeuwes puts it, or whether it reflects forms or top–down contingent processing (cf. Becker, 2008a). Likewise, an equally intense discussion concerns whether inter-trial priming of attentional capture reflects a form of feed-forward priming of stimulus features in trial $n+1$ by those of the preceding target in trial *n*, or whether the effect reflects retrieval of stimulus features of trial *n* during the processing of trial $n+1$ (cf. Becker, 2008b). In conclusion, Theeuwes uses his speed assumption inconsistently, with the effect of discarding some studies while including others, and without a clear connection to his major theoretical tenets in the case of inter-trial priming.

Next, we will show that Theeuwes (2010) also selectively reviewed the evidence for the time course of the effects of top–down control over attention. According to Theeuwes, all studies of top–down controlled forms of attentional capture are such that it would be clear that the effects are too late to occur in the feed-forward phase. This, however, is just a consequence of disregarding a large body of evidence that top–down control of attention is typical for the feed-forward phase of visual processing.

It is true that Folk et al. (1992) showed more attentional capture by top–down matching than non-matching distractors only with relatively long distractor–target intervals. However, Ansorge and Heumann (2003) and Ansorge and Horstmann (2007) showed stronger attentional capture by top–down matching distractors than by non-matching distractors with zero intervals between distractor and target. Thus, it is not true that a positive interval between irrelevant distractor and relevant target is necessary to observe top–down controlled attentional capture.

In addition, Ansorge and Horstmann (2007) and Ansorge, Horstmann and Carbone (2005) studied attentional capture effects by matching and non-matching distractors as a function of the search times of their participants: among the fastest search times these authors found only top–down controlled attentional capture, but no exogenous-capture by irrelevant and non-matching singletons at all. If anything, exogenous attentional capture by the non-matching singletons built up over time, that is, was stronger among the slower search times.

ERP (event-related potential) studies confirmed this picture. These studies investigated the time course of attention on a millisecond-by-millisecond basis with the help of differences in contralateral and ipsilateral potentials over parieto-occipital electrodes elicited by the capture of attention towards a stimulus. These studies failed to find early capture by non-matching singletons and only confirmed top–down contingent capture (cf. Eimer & Kiss, 2008; Eimer, Kiss, Press, & Sauter, 2009; Kiss, Jolicoeur, Dell'Acqua, & Eimer, 2008). It might be objected that some of these potentials are too late and do not provide an exhaustive measure of attentional capture (Theeuwes, 2010). However, top–down controlled feature-dependent attentional capture was found in ERP components even within the feed-forward phase, 100 ms after distractor onset (Zhang & Luck, 2009), and even the late ERP components are more sensitive for attentional capture during the feed-forward phase than mean RTs, on which Theeuwes mostly bases his arguments for exogenous attentional capture.

One major source of evidence for top–down controlled attentional capture during the feed-forward phase was completely ignored by Theeuwes (2010): results of backward-masking studies. The method of backward masking isolates the feed-forward phase of visual processing from later feed-back phases (Lamme & Roelfsema, 2000). Numerous backward-masking studies have demonstrated that a masked stimulus' shape and color can be processed (e.g., Klotz & Neumann, 1999; Vath & Schmidt, 2007). Crucially, these features can be also used for top–down controlled attentional capture during the feed-forward phase of visual processing. Ansorge and Neumann (2005), for example, used black or red targets. These authors found that if the participants searched for black targets backward-masked black singleton distractors captured their participants' attention, but if the participants searched for red targets the same black backward-masked singleton distractors did not capture attention. Scharlau and Ansorge (2003) likewise used top–down matching singletons and non-matching singletons as backward-masked distractors, and demonstrated that attentional capture was stronger with top–down matching than with non-matching singleton distractors.

In addition, deallocation of attention with the backward-masked distractors was not only unlikely in the first place, but also empirically ruled out as the responsible factor with a more ERP measure. This was done by Woodman and Luck (2003; for related results, see also Jaśkowski, van der Lubbe, Schlotterbeck, & Verleger, 2002). These authors found that if a backward-masked matching singleton and a backward-masked non-matching singleton were presented concomitantly, one left and the other right of fixation, participants' attention was only captured by the matching singleton. Only this singleton elicited an N2pc, that is, a contra-ipsilateral activity difference at occipito-parietal electrodes, the masked non-matching singleton did not.

These findings clearly show that if the feed-forward phase of visual processing is isolated, we only find evidence for top–down controlled forms of attentional capture. Top–down controlled attentional capture during the feed-forward processing phase is probably brought about by biased competition (Reynolds, Chelazzi, & Desimone, 1999). According to the biased-competition model, the top–down set operates via increasing the sensitivity of visual brain areas devoted to the processing of specific relevant target features, such as particular colors. As a consequence of the decrement of these sensitivity thresholds for particular features in advance of visual perception, attentional capture by visual input can then be already biased in the direction of relevant features, right from stimulus onset on (cf. Bichot, Rossi, & Desimone, 2005; Zhang & Luck, 2009).

We want to emphasize that we think that similar top–down controlled search settings improve singleton capture where singletons are relevant, so that an equally fast mechanism operates during the feed-forward phase when singletons are relevant (cf. Donk & van Zoest, 2008; Ogawa & Komatsu, 2004; Zhaoping, 2008). Performance in many experimental situations probably reflects mixtures of top–down controlled singleton search and top–down controlled feature search modes.

By contrast, exogenous forms of attentional capture by singletons seem to require more time and build up over time. These forms of attentional capture would be typical for long stimulus displays that do not require the precise synchronization of particular top–down search sets with stimulus onset so that participants could idle and pick up additional information of no actual use. Exogenous forms of attentional capture could also be typical of stimulus displays that vary substantially over time so that participants have good reasons to search for new correlations between relevant and irrelevant features for the improvement of their already existing top–down controlled search settings. It is of course a matter of taste whether one wants to call such more time-variable sorts of attentional capture in the service of learning 'exogenous', but we think the term 'exogenous' capture is fitting because these forms of attention do not necessarily require intentional supervision and conscious registration on the side of the observer (e.g., Chun & Jiang, 2003).

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