Bottom-up and top-down attention are independent

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What is the relationship between top-down and bottom-up attention? Are both types of attention tightly interconnected, or are they independent? We investigated this by testing a large representative sample of the Dutch population on two attentional tasks: a visual search task gauging the efficiency of top-down attention and a singleton capture task gauging bottom-up attention. On both tasks we found typical performance—i.e., participants displayed a significant search slope on the search task and significant slowing caused by the unique, but irrelevant, object on the capture task. Moreover, the high levels of significance we observed indicate that the current set-up provided very high signal to noise ratios, and thus enough power to accurately unveil existing effects. Importantly, in this robust investigation we did not observe any correlation in performance between tasks. The use of Bayesian statistics strongly confirmed that performance on both tasks was uncorrelated. We argue that the current results suggest that there are two attentional systems that operate independently. We hypothesize that this may have implications beyond our understanding of attention. For instance, it may be that attention and consciousness are intertwined differently for top-down attention than for bottom-up attention.

Introduction

The senses are continuously bombarded with a multitude of sensory impressions. A key challenge is to select which impressions are relevant and which inputs should be ignored. This process of selecting a subset of the input, and ignoring the rest, is referred to as attention (Broadbent, 1958; Desimone & Duncan, 1995; Neisser, 1967; Treisman, 1960). Within such a conceptual scheme, a central question of debate has been whether the moment of selection is early or late (Broadbent, 1958; Deutsch & Deutsch, 1963).

Note that described like this, attention seems to be a unitary phenomenon. It seems that there is one selection mechanism, and this selection mechanism filters all incoming input.

However, currently, two types of attention are commonly distinguished in the literature: bottom-up and top-down attention, or *stimulus-driven* and *goal-oriented* attention (Carrasco, 2011; Corbetta & Shulman, 2002; Desimone & Duncan, 1995; Kastner & Ungerleider, 2000). Top-down attention refers to the voluntary allocation of attention to certain features, objects, or regions in space. For instance, a subject can decide to attend to a small region of space in the upper-left corner or to all red items. Both cases are examples of top-down attention, the first of top-down spatial attention, the latter of top-down feature attention (Beauchamp, Cox, & Deyoe, 1997; Bressler, Tang, Sylvester, Shulman, & Corbetta, 2008; Giesbrecht, Woldorff, Song, & Mangun, 2003). On the other hand, attention is not only voluntarily directed. Salient stimuli can attract attention, even though the subject had no intentions to attend to these stimuli (Schreij,

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Owens, & Theeuwes, 2008; Theeuwes, 1991, 1992). For instance, if a subject is engaged in a conversation, but a loud bang occurs, this bang may attract attention. Or, in the visual domain, someone may be looking for red items, but an unexpected, sudden appearance of a nonred object may inadvertently draw the attention of the subject.

The similarity in top-down and bottom-up deployments of attention is that, although the reason for attentional deployment is different, the effects are largely the same. In both cases, the attended objects receive preferential processing. In both cases, this leads to an increased neural response, which has functional consequences, such as better memory storage (Buschman & Miller, 2007; Ciaramelli, Grady, & Moscovitch, 2008; Reynolds & Chelazzi, 2004).

However, there are also important differences between both types of attention. Top-down attention is also referred to as endogenous or sustained attention, and bottom-up attention is commonly typified as exogenous or transient attention (Carrasco, 2011). This difference in nomenclature is employed for a good reason: Top-down attention is called endogenous because, unlike bottom-up attention (which is automatic/involuntary), it is under clear voluntary control. Importantly, top-down attention is called sustained, since subjects typically direct their top-down attention at objects, features, or regions in space for sustained periods of time, whereas bottom-up attention is transiently captured. Moreover, top-down attention seems to take longer to deploy than bottom-up attention, approximately 300 and 100–120 ms, respectively (Cheal, Lyon, & Hubbard, 1991; Hein, Rolke, & Ulrich, 2006; Ling & Carrasco, 2006; Liu, Stevens, & Carrasco, 2007; Muller & Rabbitt, 1989; Nakayama & Mackeben, 1989; Remington, Johnston, & Yantis, 1992).

Furthermore, although some of the effects of top-down and bottom-up attention are similar, there are also important differences. Yeshurun and Carrasco (1998) had subjects detect a texture-defined target with a specific orientation on a background of orthogonal orientation. In such a task, performance does not always peak when the target is presented foveally, but depending on the spatial scale of the target, on certain eccentric locations (Gurnsey, Pearson, & Day, 1996; Joffe & Scialfa, 1995; Kehrer, 1989; Morikawa, 2000). It appears that this is caused by the fovea being most sensitive to high spatial frequencies, whereas eccentric parts of the retina are more sensitive to lower spatial frequencies (Kehrer, 1989). Interestingly, Yeshurun and Carrasco (1998) employed an exogenous cue to direct bottom-up attention to the target location. This seemed to always increase the perceived spatial resolution of the target, causing a *detrimental* effect on task performance when the target location was too near a foveal location. Importantly, in a similar setup, top-down attention only increased spatial resolution when this was beneficial for the task at hand (Yeshurun, Montagna, & Carrasco, 2008). This then is a clear example where bottom-up attention rigidly causes a certain effect (increased spatial resolution), whereas top-down attention may be more flexible (only increase spatial resolution when it is beneficial). The differential influence of top-down and bottom-up attention is also observed in temporal order discrimination. Bottom-up attention seems to impair it; top-down attention seems to enhance it (Hein et al., 2006).

Also in detecting second-order texture contrasts, differential effects are found. Both types of attention enhance second-order contrast sensitivity, but the effects of bottom-up attention are driven by second-order spatial frequency content, whereas the effects of top-down attention are independent of this (Barbot, Landy, & Carrasco, 2012).

With regards to the interaction between attention and working memory top-down and bottom-up attention also seem to play different roles. Top-down attention seems to leave the *meridian effect* intact. The meridian effect is the phenomenon that performance drops when the attended location is separated from the memory target by more vertical or horizontal crossings (Botta, Santangelo, Raffone, Lupianez, & Belardinelli, 2010), whereas bottom-up attention cancels the meridian effect (Rizzolatti, Riggio, Dascola, & Umilta, 1987).

Another example is that top-down attention can be flexibly employed depending on differential *cue* validity, whereas bottom-up attention seems to lack this flexibility and is always employed to the same extent irrespective of cue validity (Giordano, McElree, & Carrasco, 2009).

A final noteworthy example of a differential effect of bottom-up and top-down attention is observed in the so-called inhibition of return phenomenon (IOR; Posner & Cohen, 1984), where attention first facilitates processing at a location, followed by inhibited processing at this same location. Importantly, IOR seems only to occur when bottom-up attention is involved (Peelen, Heslenfeld, & Theeuwes, 2004).

Importantly, note that it may also be that within top-down (and perhaps also bottom-up) attention, different subdivisions can be made. Top-down attention can be directed at a location, or at specific features. For instance, one may attend to the center of the screen, or one may attend to any red item. In the latter case different disconnected areas in space may be selected. This does not only have spatial consequences, but seems also to affect temporal qualities: Spatial attention may be employed faster than featural attention, i.e., it seems to take 150–300 ms to employ spatial attention and 300–500 ms to employ featural attention (Liu et al., 2007).

So there is ample evidence that bottom-up and top-down attention can have differential effects. However, this does not necessarily imply that both types of attention do not share certain key properties or are even caused by the same underlying mechanism. For example, jumping is different from running in many respects, but nonetheless both are caused by the same underlying system.

Thus, despite all the differential effects, it is still unclear whether bottom-up and top-down attention are caused by two independent systems, or not. An indication that top-down and bottom-up attention are caused by differential mechanisms is that bottom-up, but not top-down, attention is already present in the most simple species, such as fruit flies (Van Swinderen, 2007; Van Swinderen et al., 2009). This then would suggest that bottom-up attention is a more primitive form of attention, and top-down attention a newer form.

However, there are also indications that, in humans at least, both systems are integrated. Neglect normally comes about by lesions to cortical areas, specifically the right parietal lobes (Smania et al., 1998; Vallar, 1993, 1998; Vallar & Perani, 1986). If both systems are independent, then it could be expected that in neglect, top-down attention is affected, but bottom-up attention is not. However, it seems that both types of attention are strongly reduced in the neglected field.

Furthermore, studies into eye movements also suggest a strong degree of integration of both types of attention. When attention is influenced by both bottom-up and top-down factors, one could expect a horse-race, if both types of attention are independent. So, if top-down attention wants to direct the eyes to location A, and bottom-up attention is attracted to location B, it could be expected that the eyes go to location A on some trials, and to location B on others. However, this is not what happens. In such a case, the eyes typically go to a location somewhere between A and B (Godijn & Theeuwes, 2002). This finding is congruent with the notion that there is only one attentional system, or at least that the attentional systems operate in an integrated manner.

Importantly then, the evidence so far is not conclusive: Even if there would be only one attentional system, it could still respond differently depending on the cause of its deployment (urgent or less urgent action for instance). Furthermore, bottom-up attention may be a philogenetically older system, but the brain as a whole must remain an integrated organ. Whether over the course of evolution newer systems are independent from older systems is (also) determined by selection pressure and not only phylogenetic order. Also, the evidence regarding neglect patients is not unambiguous, some bottom-up capture of attention does seem to break through the neglect (Vuilleumier & Schwartz, 2001). Finally, the integrated eye movement output could point to an integrated attentional system, but the integration could also occur later (for instance in the superior colliculus), after two independent systems have given their respective inputs, or, since the temporal dynamics may differ between both types of attention, it could be that the bottom-up system affects the trajectory of the eye movement first, and the top-down system affects it later, creating an eye movement affected by both influences.

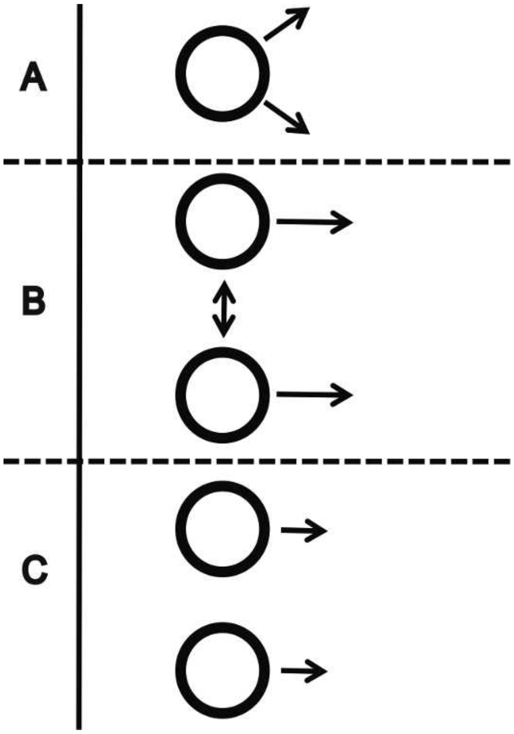

Figure 1. We are essentially considering three possibilities. Either top-down and bottom-up attention originate from the same system (A), or they originate from different, *interdependent* systems (B), or they originate from different, independent systems (C). We argue that if bottom-up capture and top-down guidance are correlated, then this supports options (A) or (B); no correlation would be more congruent with option (C).

Thus, a key question remains whether the human brain essentially has one attention center, controlling both top-down and bottom-up attention, or whether there are essentially two attention systems, one controlling top-down and one controlling bottom-up attention. When we consider the psychometric properties of these two attentional systems, we can distinguish between three different types of models.

It is possible that one mechanism produces both top-down and bottom-up attention (see Figure 1A). Alternatively, it could be that there are two mechanisms underlying both types of attention, but that both mechanisms strongly influence each other (see Figure 1B; Van Der Maas et al., 2006). In both situations, one would expect that performance on a top-down attention task correlates with performance on a bottom-up attention task.

Finally, it is possible that not only are both types of attention produced by two different systems, but that both mechanisms also operate independently.

In the first two scenarios, top-down attention (measured with a visual search task) and bottom-up attention (measured with a singleton capture task) should be strongly correlated. If both types of attention are indeed strongly correlated, then performance on both tasks should also be strongly correlated. So, either people who are efficient in deploying top-down attention should be *less* susceptible to irrelevant distractors, or *more*. However, the main point is that if the two types of attention are interdependent, this should be reflected by a correlation in how efficient top-down attention can be deployed, and how easily bottom-up attention is captured. For instance, it could be that people who are more efficient in guiding their attention are more in control of their attentional deployments in general, and thus are less distractable (i.e., are less susceptible to salient distractors). In that case we would expect to find a negative correlation between search efficiency and amount of capture. It seems more far-fetched to find a positive correlation between search efficiency and distractibility, but this cannot be excluded beforehand. For instance, perhaps people who are better at deploying top-down attention are just better at deploying attention generally, and thus also better at deploying bottom-up attention. In that case one would expect a positive correlation between search efficiency and susceptibility to bottom-up distractors. Importantly, if the two types of attention are interdependent, some type of correlation between search efficiency and distractibility is expected. Only in the third scenario, where top-down attention and bottom-up attention operate independently, is it expected that performance on the top-down attention task is uncorrelated to performance on the bottom-up task. So the predictions simply boil down to this: If the first or second scenario is correct, we expect to find a correlation between task performance on both tasks. However, if the third scenario is correct, we expect to find no such correlation.

In the current study, we investigated whether performance on a top-down attention (measured with a visual search task) and bottom-up attention task (measured with a singleton capture task) are correlated in a large, representative sample (for the cohort of 20 to 25 years of age) of the Dutch population. We measured top-down attention and bottom-up attention using two different tasks. The use of two different tasks avoids spurious correlations based on the similarity of testing. For instance, if in both cases we would use a multiple-object tracking task, and then manipulate which type of attention is employed, then there is a danger of finding correlations just because some people are better in multiple-object tracking than others, and this ability may then affect both types of attentional deployment in this specific setting. To test top-down attentional control, we employed a conjunction visual search task (participants search a rotated T among rotated Ls), which required the deployment of top-down attention in order to find the target (Wolfe & Horowitz, 2004). The dependent measure in this task is the search slope: How fast does attention move from item to item? The search slope is thought to reflect the efficiency of top-down attention, since attention is quickly steered around based on top-down goals. Note that the intercept is not considered to be a reliable measure of top-down attention, since the intercept indicates how fast someone is when no attentional shifts have yet occurred. Note furthermore that although the search slope is considered to reflect top-down attention in general (Wolfe & Horowitz, 2004), this may reflect several different aspects of top-down attention, such as how quickly attention can be deployed, how quickly it can be disengaged, and how fast items within an attentional window can be compared to the target template.

A singleton capture paradigm was used to test bottom-up capture (Theeuwes, 1992). In this task participants searched for a uniquely colored shape (in our case, a diamond among circles), while at some trials an irrelevant singleton was present (in our case: one of the circles had a unique color). The dependent measure in this case was how much slower subjects were when the irrelevant singleton was present. This is thought to reflect how much bottom-up attention is drawn to the irrelevant singleton (Hickey, McDonald, & Theeuwes, 2006; Theeuwes & Godijn, 2002). Again, the drawing of bottom-up attention may consist of more than one process. It may reflect how often bottom-up attention is drawn, how long it is engaged, and how long it takes to redeploy it. Note that although in the singleton capture paradigm, subjects also have a search goal, the irrelevant singleton is never the goal. Therefore, we argue that this paradigm is an especially reliable measure of bottom-up attention. Not only is it not beneficial to attend to the irrelevant singleton (which is normally considered to be enough to avoid the deployment of top-down attention, e.g., Hein et al., 2006; Jonides & Yantis, 1988; Yantis & Jonides, 1984), it is even *detrimental*, making it virtually certain that subjects will not voluntarily (or in other words in a top-down manner) attend to the irrelevant singleton.

Since we are dealing with a very large sample of subjects ($N = 936$), and we have two clear competing hypotheses, we apply Bayesian statistics to be able to also evaluate the likelihood of there being no correlation between task performances. Importantly then, this allows us to find evidence for or *against* the existence of a correlation between both measures.

The current set-up provides two important strongpoints: It is a large and representative sample of the Dutch population (in terms of gender and educational level), and we have two well-tested, independent tasks that serve as a benchmark for experiment validity (does each task produce a normal pattern of results?).

To preview our results: Both the visual search and attentional capture task produced the expected pattern of results. Importantly, we found that there is very strong evidence supporting the hypothesis that the performance on bottom-up and top-down attentional tasks is NOT correlated. We argue that this suggests that attention is not a unitary phenomenon, and top-down and bottom-up attention should be thought of as two independent attentional systems that also operate, at least within the ranges tested with singleton capture and visual search, independently.

Method

Subjects

In this experiment, 936 subjects participated (489 females; age range 20–26 years; mean age 22.85 years, *SD* 1.7 years), all having normal or corrected-to-normal vision. All subjects gave their written informed consent to participate in the study, which was approved by the local ethics committee of the University of Amsterdam. Subjects received financial compensation or course credits for their participation. Subjects were recruited from different backgrounds and were representative of the Dutch population in several ways (IQ, gender, and socioeconomic background).

Equipment and stimuli

We tested subjects on two experiments, a visual search task and an attentional capture task. In both cases stimuli were displayed on a 22-in. ViewSonic LCD-display (type 2268WM, ViewSonic Company, London, UK) at a refresh rate of 60 Hz. The software package Presentation version 9.7 (NeuroBehavioral Systems, Inc., Albany, CA) was used for the layout and the timing of the experimental trials. Subjects were seated 55 cm from the monitor, thus the total viewing angle of the display spanned 40° × 22°.

In the visual search task the display consisted of five or nine rotated Ls (green, 10.9 cd/m^2, Commission Internationale d'Eclairage [CIE] *x*-, *y*-coordinates: 0.293, 0.606; 1.2° × 0.7° in size), and one upright or downward T (green, 10.9 cd/m^2, CIE *x*, *y*: 0.293, 0.606; 1.2° × 0.7° in size). The presented stimuli were equally spaced on an imaginary circle (with a radius of 5.5°) around the fixation spot (white, 37.9 cd/m^2, CIE *x*, *y*: 0.287, 0.315, radius: 0.065°) on a black background (see Figure 2).

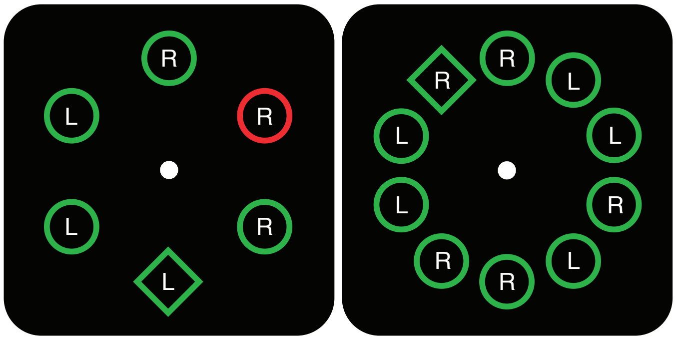

Figure 2. Examples of the attentional capture task. Participants had to indicate the identity of the letter inside the diamond. The left panel depicts a distractor present trial with set size 6; the right panel depicts a distractor absent trial, with set size 10.

In the attentional capture task, the display consisted of one diamond (green, 10.9 cd/m^2, CIE *x*, *y*: 0.293, 0.606; distance corner to center: 1.32°), and five to nine circles (all, or all but one of them, green, 10.9 cd/m^2, CIE *x*, *y*: 0.293, 0.606; radius: 1.05°). In this task one of the circles could be the singleton distractor, in which case it would be red, rather than green (10.5 cd/m^2, CIE *x*, *y*: 0.641, 0.341). Within each shape was the letter "L" or the letter "R" (white, 37.9 cd/m^2, CIE *x*, *y*: 0.287, 0.315; 0.35° × 0.6° in size). The presented shapes were equally spaced on an imaginary circle (with a radius of 5.5°) around the fixation spot (white, 37.9 cd/m^2, CIE *x*, *y*: 0.287, 0.315, radius: 0.065°) on a black background (see Figure 3).

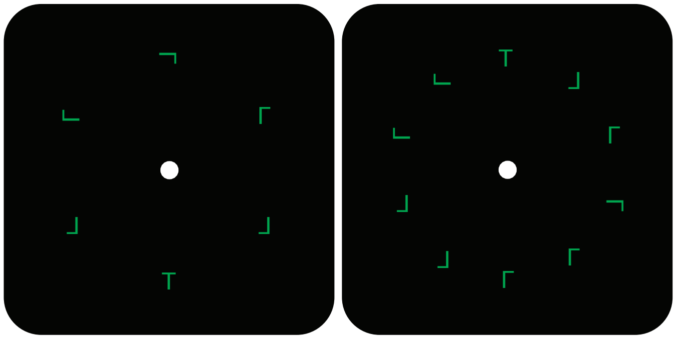

Figure 3. Examples of the visual search task. Participants indicated whether the T was upright (left panel) or downwards oriented (right panel). Set size was 6 (left panel) or 10 (right panel).

Trial design

In the visual search task participants searched for an upright or downwards T, among rotated Ls. They indicated the orientation of the T by pressing "Z" or "M." They were instructed to react as quickly and accurately as possible. On half of the trials there were five rotated Ls, on the other half of the trials there were nine rotated Ls. For each set size, the T was upright on half of the trials and downwards on the other half. Trials were randomly intermixed. The Ls could be rotated in four directions (0°, 90°, 180°, and 270°). When there were five rotated Ls, four would be rotated in the four possible directions, and the one remaining L would randomly be assigned to one of the four possible rotation angles. Essentially the same held when there were nine rotated Ls: Eight Ls would be evenly distributed among the four possible rotation angles, and the remainder would be randomly assigned. The order of the rotated Ls and the T along the imaginary circle was also randomly assigned.

In the attentional capture task, participants searched for the only diamond in the display, and indicated whether there was an L or an R inside this shape (by pressing Z or M). Again, participants were instructed to react as quickly and accurately as possible. There were five circles on half of the trials, and nine circles on the other half. For each set size, on half of the trials one of the circles was the only red item in the display (to serve as a singleton distractor), while on the other half, all items were green (so there was no singleton distractor). The identity of the letter within each shape was randomly determined, with the restriction that overall, there were an equal amount of Rs and Ls present in the display. Trials were randomly intermixed.

Procedure

First, subjects performed the visual search task then they performed the attentional capture task. Both tasks consisted of two blocks of 30 trials, and each task took about 5 min to execute.

Exclusion criteria

In the visual search task we discarded trials with reaction times faster than 250 ms, or slower than 4 s. This led to the exclusion of 0.73% of the trials. Subsequently, we excluded participants with too many errors (accuracy <85%). This led to the exclusion of 8.1% of the participants. In the attentional capture task, we discarded trials with reaction times faster than 250 ms, or slower than 3 s. This led to an exclusion of 0.56% of the trials. Subsequently, we excluded participants with too many errors (accuracy <85%), or too high search slopes (>20 ms/item). This led to the exclusion of 6.1% of the participants.

We only used data from those subjects that were not excluded from either study (since there was some overlap between participants who were excluded on one or the other task, the total number of excluded participants was 12.4%).

The overall exclusion rate is rather high. However, this is partially caused by it being the composite of two separate exclusions, and partially caused by the participants, who have an Intelligence Quotient (IQ) across the entire bell curve and are mostly unfamiliar with psychophysical tasks in general. Importantly, the results are essentially unchanged when we include all participants (in that case we still do not find a significant correlation between search slope and distractor costs; Pearson: $r = 0.027$, $p > 0.4$, Spearman: $r = 0.019$, $p > 0.55$).

Results and discussion

Performance on the visual search and attentional capture tasks

In the visual search task, we computed the average search slope per participant by subtracting the average reaction time (for correct responses) on trials with set size 6 (i.e., five rotated Ls and one T) from the average reaction time (for correct responses) on trials with set size of 10, and divide this number by four to get an average search slope per item.

In the attentional capture task, we calculated both the search slope and the distractor effect. The search slope was calculated by subtracting the reaction time (for correct responses) in set size 6 from the reaction times in set size 10, and divide this number by four. We calculated the distractor effect by subtracting the reaction time (for correct responses) for distractor absent (i.e., all shapes were green) trials form distractor present trials (i.e., one circle was red).

Analyses of the performance on these tasks (see Figure 4) showed that performance of this large, representative sample mimicked typical performance on these tasks. On the visual search task there was a significant search slope of 60 ms/item, $t(819) = 58.91$, $p < 0.001$. On the attentional capture task, the salient distractor caused a significant slowing of 20 ms, $t(819) = 12.22$, $p < 0.001$, while there was only a small difference in reaction times for set size 6 and set size 10 (we found a search slope of less than 1 ms/item, which is normally considered to be parallel search); this difference was significant (difference in RT between set

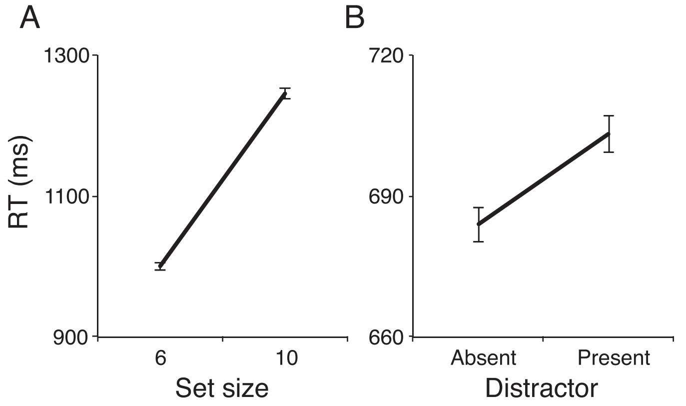

Figure 4. Performance on the visual search task (left panel) and on the attentional capture task (right panel). Reaction time (in ms) for the two set sizes (visual search task) and for distractor-absent and distractor-present trials (attentional capture task) is depicted. *SE* bars are depicted for each point. The tasks produced typical results. In the visual search task participants took longer to find the target when the number of distractors increased. In the attentional capture task the irrelevant distractor caused a slowing of response.

	Slope, search	Slope, capture	Intercept, search	Intercept, capture	Distractor costs
Slope in search task					
r		0.025	−0.732	0.053	0.006
p		0.477	<0.001	0.13	0.866
Slope in capture task					
r	0.025		−0.077	−0.638	−0.028
p	0.477		0.03	<0.001	0.431
Intercept, search task					
r	−0.732	−0.077		0.285	0.051
p	<0.001	0.03		<0.001	0.144
Intercept, capture task					
r	0.053	−0.638	0.285		0.152
p	0.13	<0.001	<0.001		<0.001
Distractor costs					
r	0.006	−0.028	0.051	0.152	
p	0.866	0.431	0.144	<0.001	

Table 1. An overview of correlations between slopes, intercepts, and capture costs. All values are based on Pearson correlations.

sizes 6 and 10: 3.7 ms, $t[819] = 3.72$ $p < 0.001$). Accuracy patterns reflected reaction time patterns. In the attentional capture task, accuracy trended to be higher when no distractor was present (94.43% correct for no distractor present, 94.15% for distractor present, $t(819) = 1.87$, $p = 0.06$), and accuracy was marginally higher for set size 6 (94.46% correct for set size 6, 94.11% correct for set size 10, $t[819] = 2.49$, $p = 0.01$). In the visual search task accuracy was higher for set size 6 (94.22% correct for set size 6, 92.82% correct for set size 10, $t[819] = 6.19$, $p < 0.001$). Thus, speed-accuracy trade-offs can be excluded.

Correlation visual search and attentional capture

There was no correlation between search efficiency and attentional capture caused by a singleton distractor (Pearson: $r = 0.006$, $p > 0.85$; Spearman's rho: $r = -.004$, $p > 0.9$) in this large, representative sample of the Dutch population. For completeness we will also report the results of other possible correlations in this data set. Note that these other correlations should be taken as exploratory results (we did not explicitly set out to test them). We have looked at possible correlations between search slope in the visual search task, search slope in the attentional capture task, intercept in the visual search task (calculated by taking the difference in reaction time between set size 10 and 6, multiplying this difference by 1.5, and subtracting that from the reaction time at set size 6: This indicates how fast reaction times are when no items are present), intercept in the attentional capture task, and attentional capture caused by a distractor. See Table 1 for an overview of these results. Note that the significant negative correlation between slope and intercept in both the search task and the attentional capture task may have a trivial explanation due to how slopes and intercepts are calculated: Randomly elevated search times in set size 10 and randomly lowered search times in set size 6 will cause the search slope to rise, but the intercept to drop. Similarly, randomly lowered reaction times in set size 10, or randomly elevated reaction times in set size 6 will decrease the search slope, but raise the intercept. In other words: any random fluctuation in reaction times will cause a negative correlation between search slope and search intercept.

Furthermore, note that something resembling a cluster of correlations seems to arise between search intercept, capture intercept and attentional capture. Speculatively, we hypothesize that this may be due to overall vigilance or general intelligence (also referred to as *g*) affecting all these measures.

After calculating the correlation between search slope and the attentional capture caused by a distractor using standard correlational measures, we proceeded by applying Bayesian statistics (Jeffreys, 1961; Shiffrin, Lee, Kim, & Wagenmakers, 2008; Wetzels, Raaijmakers, Jakab, & Wagenmakers, 2009; Wetzels & Wagenmakers, 2012) to test whether the data provided proof *for* or *against* the existence of a correlation between both performances (for this analysis we have dismissed the other correlation tests, and only considered a possible correlation between search efficiency and attentional capture caused by a distractor). The

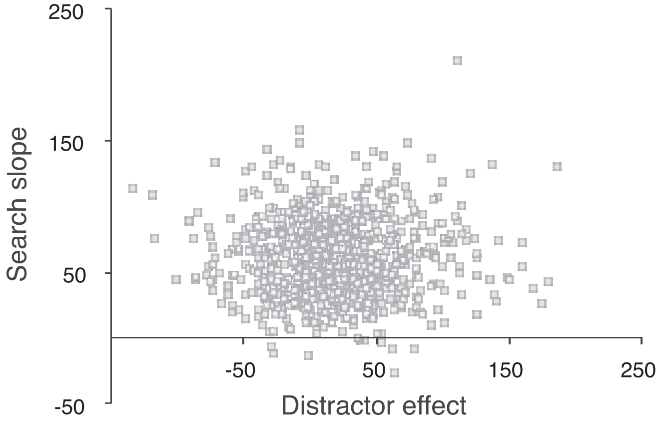

Figure 5. A scatterplot of distractor effect and search slope, per participant. Distractor effect (in ms) is depicted along the *x*-axis, search slope per item (in ms) is depicted along the *y*-axis. So if, for a participant, the singleton distractor caused a slowing of 200 ms, and this participant had a search slope of 150 ms per item, her data point would show up in the top-right corner. As can be seen in this plot, there appears to be no correlation between distractibility and search efficiency.

final result of this analysis yields a Bayes Factor (BF). This factor indicates how likely the observed data are given H_0 / how likely it is to find the data if H_a is true. Here we define H_0 as the hypothesis that there is no correlation between performance on both tasks, and H_a as the hypothesis that such a correlation does exist. So, a BF of 10 indicates that it is ten times more likely to observe the found data if there is no correlation than if there is one.

Our calculation is based on the linear model of Wetzels and Wagenmakers (2012), which differs slightly from the Bayesian correlation test suggested by Jeffreys (1961). This calculation yielded very strong evidence for the null hypothesis. Pearson's correlation yields a BF of 35.4; we also calculated the BF based on Spearman's correlation, although this rank correlation does not obey the linearity assumed in Wetzels and Wagenmakers's (2012) model. This speculative calculation yields a BF of 35.7. See Figure 5 for a scatter plot of the correlation between search slope and distractor effect and Figure 6 for an overview of how the BF developed as the number of participants increased. We therefore conclude that there is strong evidence for an absence of a correlation between visual search and attentional capture, and therefore, against a correlation between top-down and bottom-up attention. Note that differences in strategies are not a likely explanation for the absence of correlation. For instance, it could be that some subjects try to ignore the irrelevant distractor, while others do not bother with this. However, this is unlikely for two reasons. First, previous research suggests that attending to the irrelevant singleton may not be under voluntary top-down control (Pinto, Olivers, & Theeuwes, 2005; Theeuwes, 2004; note that this is an additional reason as to why this paradigm is an especially good measure of bottom-up attention), so subjects cannot employ different strategies, even if they wanted to. Second, the tasks were so basic and the goals so limited that in both cases there was little room for different strategies. In the visual search task, top-down attention had to be employed as efficiently as possible to find the target as quickly as possible. In the singleton capture paradigm, the irrelevant singleton had to be ignored as much as possible to create optimal task performance.

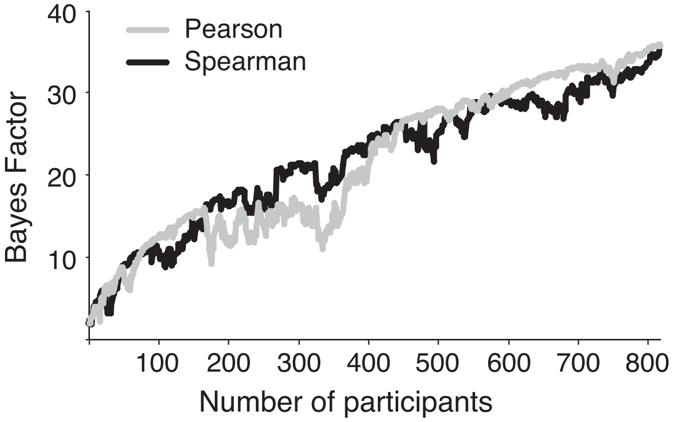

Figure 6. The development of the BF with an increasing number of participants. The rising BF indicates that as evidence accumulates, it becomes increasingly more likely that the null hypothesis is valid.

General discussion

We investigated whether attention is produced by two independent systems by correlating performance on a top-down visual search task to performance on a bottom-up capture task. We tested a large sample, to optimize the power of our design, so that we could find evidence *for* or *against* such a correlation. Both tasks produced a typical pattern of results—i.e., a significant search slope, and significant capture by the irrelevant distractor. Importantly, we found strong evidence *against* any correlation between search efficiency and susceptibility to attentional distraction.

It is unlikely that the absence of this correlation is due to a lack of power, or a weak signal to noise ratio. We found all the expected effects in the tested tasks. Even more, in the attentional capture task we even found a significant search slope of less than 1 ms/item. In most experimental setups, effects of this magnitude are not reliably detected.

Thus, the current results suggest that there are essentially two attentional systems that operate independently. One system controls the deployment of top-down attention, while the other system regulates attentional reactions to salient external events. As pointed out in the Introduction, the current research is not the only, or the first, to investigate this issue. Furthermore, we are also not the only study to find evidence for the notion that there are two independent attentional systems. Thus, the current study should be seen as part of a larger body of research (Botta et al., 2010; Hein et al., 2006; Yeshurun & Carrasco, 1998; Yeshurun et al., 2008) that supports the hypothesis that top-down attention and bottom-up attention are essentially different.

Primitive versus modern system

Is it really plausible that there are two independent attentional systems? One point of view could be that bottom-up attentional capture is a very primitive phenomenon. As mentioned earlier, even in fruit flies some type of attentional capture seems to occur (Van Swinderen, 2007; Van Swinderen et al., 2009). So perhaps, we are to think of attentional capture as a type of "knee-jerking" reaction, a very primitive orienting response that can essentially be carried out in the earliest stages of visual processing. Or in other words, perhaps bottom-up capture can already be accomplished on the basis of information provided by the initial response to incoming stimuli, the so-called "feed-forward" sweep (Lamme, 2003; Lamme & Roelfsema, 2000).

Top-down attention, on the other hand, is controlled by cortical systems (Corbetta, Kincade, Ollinger, McAvoy, & Shulman, 2000; Hopfinger, Buonocore, & Mangun, 2000; Kastner, Pinsk, De Weerd, Desimone, & Ungerleider, 1999) that can select information on the basis of a combination of several sources of input and a variety of goals and priorities. Moreover, such a selection process should be able to learn from past experiences, in order to optimize the selection process. This adaptability of top-down attention can indeed be seen in several situations. For instance, although dynamic items are very strong captors of attention (Jonides & Yantis, 1988; Yantis & Jonides, 1984), top-down attentional control can adjust to this and search efficiently for static objects among different types of dynamic distractors (Pinto, Olivers, & Theeuwes, 2006, 2008).

Contingent attentional capture

The notion of two independent attentional systems may also have implications for the long-going debate regarding contingent attentional capture (Belopolsky, Schreij, & Theeuwes, 2010; Folk, Remington, & Wright, 1994; Hickey et al., 2006; Lien, Ruthruff, Goodin, & Remington, 2008; Remington, Folk, & McLean, 2001; Schreij et al., 2008; Theeuwes, 1992). Proponents of the contingent capture hypothesis argue that attentional capture is never truly bottom-up, since top-down settings always affect whether certain items capture attention (Folk et al., 1994). However, the opponents of this hypothesis argue that certain stimuli capture attention irrespective of top-down goals. In their view top-down goals can only exert an effect at a later stage, *after* attentional capture has occurred—for instance, by determining attentional dwell time (Theeuwes, 2010).

The current results suggest that bottom-up and top-down attention are not controlled by the same system. This is in line with the notion that bottom-up capture is independent from top-down attentional control, thus opposing the contingent capture hypothesis. Perhaps bottom-up attention is very quickly deployed, in a knee-jerking fashion, during the feedforward sweep of incoming sensory information through the brain (so in the first 100–150 ms). Top-down attention may only be able to play a role at later stages of information processing, perhaps during the stage where neural feedback loops start to play an important role (after 100 ms).

Attention and consciousness

There is a lively debate regarding the role of attention for consciousness (Baars, 2002; Block, 2007, 2011; Cohen & Dennett, 2011; Koch & Tsuchiya, 2007; Lamme, 2004). The two attentional systems notion may also have implications for this topic. Bottom-up attention is more automatic and less flexible than top-down attention. Moreover, bottom-up attention seems to be much faster than top-down attention. The sluggishness and the flexibility of top-down attention suggests that top-down attention is under conscious control, and thus not a cause, but an effect of consciousness. On the other hand, the fast influence of bottom-up attention makes it a more likely candidate to be a causal factor for consciousness. Support for this differential influence on consciousness comes from different angles.

First, there seems to be support for the notion that consciousness arises when the neural feedback stage starts (Lamme & Roelfsema, 2000; cf. Roelfsema, Scholte, & Spekreijse, 1999). If bottom-up attention indeed takes place during the feedforward stage (which precedes the feedback stage), while top-down attention occurs after the feedback stage, then this would support the notion that only bottom-up attention can play a role in causing consciousness.

Second, as put forward by Tsuchiya, Block, and Koch, (2012; in reply to Cohen, Cavanagh, Chun, & Nakayama, 2012) and Chica and Bartolomeo (2012; importantly connected to Chica, Botta, Lupianez, & Bartolomeo, 2012; Chica et al., 2011; Chica, Lasaponara, Lupianez, Doricchi, & Bartolomeo, 2010), there is psychophysical evidence from objects presented in isolation and stimuli presented near threshold that top-down attention does not, but bottom-up attention does, affect consciousness (however, see also Hsu, George, Wyart, & Tallon-Baudry, 2011). A recent investigation also suggests that bottom-up attention can increase conscious recollection of previously presented stimuli (Sergent et al., 2013), although note that similar effects have been found with top-down attention (Landman, Spekreijse, & Lamme, 2003; Pinto, Sligte, Shapiro, & Lamme, in press; Sligte, Scholte, & Lamme, 2008).

Importantly then, perhaps bottom-up attention is more important for consciousness than top-down attention. This seems to be somewhat at odds with the influential "global workspace" theory (Baars, 1988; Dehaene, Kerszberg, & Changeux, 1998), which suggests an important role for top-down attention (but not necessarily bottom-up attention) in bringing about consciousness. Note furthermore, that although bottom-up attention may boost consciousness, it is unlikely to be a sufficient condition for it since there is evidence that bottom-up attention can operate in the absence of consciousness. When stimuli are invisible because of cortical damage, there still seems to be bottom-up capture of stimuli, which does not lead to the entry of these stimuli into consciousness (Kentridge, Heywood, & Weiskrantz, 1999). Moreover, stimuli can be presented as onsets (which are known to capture attention), without seemingly entering consciousness (Mack, 2003; Scholte, Witteveen, Spekreijse, & Lamme, 2006; Simons, 2000; Simons & Chabris, 1999; but see also Wolfe, 1999). Stimuli can even capture attention to such an extent that eye movements are made to these stimuli, without subjects showing any increased awareness of these stimuli, or the eye movements they have made (Theeuwes, Kramer, Hahn, & Irwin, 1998).

Conclusion

Tests of a large and representative sample of the Dutch population provide strong evidence that two types of attention, bottom-up and top-down attention, are uncorrelated. This suggests that there are two independent attentional systems controlling these types of attention. We speculate that bottom-up capture is not contingent on top-down settings, and that bottom-up attention and top-down attention are differentially linked to consciousness.

Keywords: top-down, bottom-up, search efficiency, attentional capture, visual attention

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