Feature-based attention across saccades: Pop-out in color search is spatiotopic

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Abstract

Our perception of the world remains stable despite the retinal shifts that occur with each saccade. The role of spatial attention in matching pre- to postsaccadic visual information has been well established, but the role of feature-based attention remains unclear. In this study, we examined the transsaccadic processing of a color pop-out target. Participants made a saccade towards a neutral target and performed a search task on a peripheral array presented once the saccade landed. A similar array was presented just before the saccade and we analyzed what aspect of this preview benefitted the postsaccadic search task. We assessed the preview effect in the spatiotopic and retinotopic reference frames, and the potential transfer of feature selectivity across the saccade. In the first experiment, the target and distractor colors remained identical for the preview and the postsaccadic array and performance improved. The largest benefit was observed at the spatiotopic location. In the second experiment, the target and distractor colors were swapped across the saccade. All responses were slowed but the cost was least at the spatiotopic location. Our results show that the preview attracted spatial attention to the target location, which was then remapped, and suggest that previewed features, specifically colors, were transferred across the saccade. Furthermore, the preview induced a spatiotopic advantage regardless of whether the target switched color or not, suggesting that spatiotopy was established independently of feature processing. Our results support independent priming effects of features versus location and underline the role of feature-based selection in visual stability.

Keywords Attention · Eye movements · Feature-based attention · Pop-out · Spatiotopic

Introduction

Every eye movement shifts the image on the retina and the visual system has to match pre- to postsaccadic information to stabilize the visual scene. Most studies on this transsaccadic correspondence have examined the role of spatial attention and showed that attended locations are remapped across a saccade (e.g., Rolfs, Jonikaitis, Deubel, & Cavanagh, 2011). In this

study, we aimed to determine whether feature-based attention, which processes features independently of their location, could also take part in establishing visual stability across saccades. Some studies have examined the link between the attentional deployment and the visual properties of the saccade target and found no interplay between them (Eymond, Cavanagh, & Collins, 2016; Jonikaitis & Theeuwes, 2013; White, Rolfs, & Carrasco, 2013). Here we tested feature-based selection independently of the attentional resources allocated to the saccade target. To do so, we examined the transsaccadic processing of a pop-out target, where the final locus of attention relies on the parallel processing of features.

In a singleton array, the unique element – for instance, a red square among blue squares – pops out. The selection of the pop-out target location relies on the parallel processing of features, when attention is deployed across the visual field. This early visual stage determines which location is selected as the most salient for further focal-attentional processing (Theeuwes, 2010; Treisman & Gelade, 1980). In the present study, we asked participants to perform a postsaccadic feature search task in a peripheral pop-out array presented directly at

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saccade offset. We examined whether search performance was modulated when a similar array was previewed just before the saccade. We expected that the preview of the peripheral array would provide either the salient target color or its location, or both, for postsaccadic processing. Exogenous attentional orienting to locations other than the saccade target has been previously demonstrated during saccade preparation (Castet, Jeanjean, Montagnini, Laugier, & Masson, 2006; Montagnini & Castet, 2007). We expected that the preview of the peripheral singleton just before the saccade would initiate the allocation of attention required for target selection.

We examined the nature of this allocation and used a preview of an odd-ball search array (Bravo & Nakayama, 1992) in which the target color was randomly chosen to be red or blue on each trial. At the initial stage of target selection, the unique colored element must be discovered. This feature information then guides spatial attention to the location of the target (Theeuwes, 2010; Treisman, & Gelade, 1980). To better understand the role of feature-based attention in visual stability, we examined the spatial reference frame of pop-out target processing: we tested whether the second spatially specific stage of target selection was based in retinal or world coordinates. It is also not known whether the initial parallel stage of target selection leads to any feature selectivity that could be maintained across the saccade. Specifically, a spatially (or unspatially) specific feature-based preview effect could participate (or not) in positioning the locus of attention immediately after the saccade. We conducted two experiments to test the reference frame of any preview benefit to the pop-out target processing as well as the potential transfer of feature selectivity across the saccade. We assessed the preview effect in the spatiotopic and retinotopic reference frames, first with the colors for the target and distractors maintained across the saccade, and second, with their colors swapped between them.

We first examined whether the presence of a previewed search array facilitated the positioning of spatial attention onto the target in the subsequent postsaccadic search. Studies on the transsaccadic processing of a salient location reported a postsaccadic attentional facilitation both at the same location, in spatiotopic, world-centered coordinates, and at the retinal location (Jonikaitis, Szinte, Rolfs, & Cavanagh, 2013; Mathôt & Theeuwes, 2010). Furthermore, other studies have examined the reference frame of spatial priming of pop-out (i.e., when repeating the target location in the next search trial improves search performance). In this case, a robust facilitation in the spatiotopic reference frame, and a weaker facilitation in the retinotopic reference frame have been found (Gokce, Müller, & Geyer, 2015; Tower-Richard, Leber, & Golomb, 2016).

In our postsaccadic search task, if the positioning of spatial attention is facilitated by the previewed singleton and its position is remapped across the saccade (e.g., Rolfs et al., 2011), we should find better preview benefits on reaction times when the target remains at the same spatiotopic location. If the locus

of attention is not remapped or only partially remapped we should find better performance when the target remains at the same retinotopic location. Either spatiotopic or retinotopic preview effects would suggest that the previewed singleton attracted spatial attention to its location.

Second, we examined whether any feature selectivity established by the preview array was maintained across the saccade. In our experiment, the preview just before the saccade may allow the target and distractor colors to be selected for further processing. Feature priming has been mainly studied in successive pop-out search tasks without eye movements. The classic effect is the priming of pop-out with a benefit for reaction times in the next search trial when items' colors are repeated, and with a cost when colors between target and distractors are swapped between them (Becker, Valuch, & Ansorge, 2014; Eimer, Kiss, & Cheung, 2010; Maljkovic & Nakayama, 1994).

If the preview did not encode the target and distractor colors for postsaccadic processing, the performance advantage should remain unaffected when the target and distractor colors are exchanged across the saccade. In contrast, if the previewed singleton colors are maintained across the saccade to prime the postsaccadic search, this should speed the processing of the target in the postsaccadic display. And conversely, when the target and distractor colors are swapped in the postsaccadic display, the search would resume with the wrong target and distractor colors and the search should be slowed. Particularly, a speeding up or slowing down of search performance in all reference frames would provide evidence in favor of a spatially nonspecific preview effect.

In other words, if the previewed features participate in determining the immediate postsaccadic locus of attention (a spatially specific feature effect), the cost on performance in the swapped colors experiment should be specific to one location. In contrast, if the positioning of spatial attention is facilitated independently of feature processing, the preview effect should remain with a location specific advantage in the swapped colors experiment, in addition to the nonspecific cost of the feature exchange.

Methods

Participants

Eight participants (three men, five women, including author CE) between 22 and 43 years old, with normal or corrected-to-normal vision, took part in both Experiments 1 and 2. All participants gave their informed written consent prior to participation. Paris Descartes University Review Board (CERES) approved the protocols for the study, in accordance with French regulations and the Declaration of Helsinki. The participants, except for the author CE, were naïve as to the purpose of the study and were compensated 10 euros per hour.

Apparatus and stimuli

The experiment was programmed in MATLAB, using the Psychophysics and Eyelink Toolbox extensions (Brainard, 1997; Cornelissen, Peters, & Palmer, 2002; Kleiner et al., 2007; Pelli, 1997). The stimuli were 0.75° squares displayed in red (3.96 cd/m^2 , CIE $x,y = 0.528, 0.384$) or blue (3.40 cd/m^2 , $x,y = 0.155, 0.113$) on a gray background (11.7 cd/m^2 , $x,y = 0.302, 0.345$). The fixation point was a black 0.5° -diameter circle that served as a saccade cue when it exchanged its position with one of two potential saccade targets (0.3° -diameter black dots) situated at 10° in the right and left directions. The $30^\circ \times 9^\circ$ pop-out array consisted of a 6×3 grid (Fig. 1a). Each of the 18 cells was $5^\circ \times 3^\circ$, and only one item could appear per cell. The location of an item within the cell was random. There were nine possible target cells (three vertical $\times$ three horizontal, cells filled in gray as shown in Fig. 1a). For a given vertical position, the target location was randomly assigned to one of the three cells, and the two remaining cells were occupied by a distractor, at the same position as the target within the cell (Fig. 1a). Eight other cells were then randomly chosen among the 15 remaining cells and were occupied by a distractor. The location of these distractors within a cell was random. Thus, there were 11 items in total in the display.

All stimuli were presented at a viewing distance of 51 cm on a 20-in. CRT monitor screen (spatial resolution of $1,024 \times 768$ pixels, vertical refresh rate of 120 Hz). Movements of the right eye were recorded using an Eyelink 1000 eye-tracker (SR Research Ltd., Mississauga, ON, Canada) operating at 1,000 Hz. The participant's head was stabilized by a chin and a forehead rest. Saccades were detected online. When the saccade was made to the wrong target (opposite to the required direction) or when the latency was more than 1 s,

the trial was aborted and rerun at the end of the block. Landing accuracy was checked online and participants received auditory feedback after they gave their answer. When the initial saccade ended more than 2° from the saccade target, the trial was aborted and later rerun. Manual responses were recorded with a standard keyboard. When no response was given after 2 s, a message asked the participants to respond faster, and the trial was rerun at the end of the block. Trials with an incorrect answer were rerun at the end of the block up to a maximum of three times (for a total of four presentations; see the Analyses section below).

Design and procedure

Participants made a saccade followed by a postsaccadic feature search task of a pop-out target right at saccade landing. They performed this task in two conditions that are described in detail later: with and without a preview of the search array before the saccade (Fig. 2). Each trial, with or without the preview array, began with participants fixating an open black dot at the center of the screen. Two filled black dots flanked the fixation dot at 10° eccentricity. After a variable fixation from 500 to 900 ms, the fixation dot exchanged its position with one of the flanker dots, indicating the target for the saccade. Participants were instructed to make a fast and accurate saccade toward the open black dot. Once the response saccade was detected (see the Analyses section for the online detection criterion), the search display was presented below the saccade target and the two black dots for a fixed 80-ms duration (after the saccade landed, the mean postsaccadic display duration was $52 \pm (\text{SD}) 6 \text{ ms}$). Participants had to report as quickly as possible the position of the small white horizontal bar on the unique target, either at the top or at the bottom (see Fig. 2).

Fig. 1 (a) Example of a postsaccadic pop-out array after a rightward saccade. The open circle was the saccade target and the central black dot was the fixation position before the saccade. The left black dot is the other potential saccade target. The red postsaccadic search target occupies one out of the nine potential cells that are filled in gray. In this example, the presaccadic location of the red singleton could have occupied the spatiotopic, retinotopic, or control2 location, which are indicated in parentheses. Two distractor locations were defined with respect to the search target, the eight remaining distractor locations were random. Before the saccade, the presaccadic array was identical but with two

exceptions: the white markers were absent for all items in the display, and the singleton either exchanged its position with a distractor in the retinotopic and control conditions or remained at the same spatiotopic location. The mean horizontal eccentricities for the potential presaccadic singleton and postsaccadic search target locations are indicated below the array. (b) Table of preview conditions, according to the combinations between pre- and postsaccadic locations (horizontal component of eccentricity with respect to the saccade direction). The search array illustrated in (a) is shown in bold

Fig. 2 Procedure. Participants maintained central fixation until the saccade target appeared to the left or right. The postsaccadic search display was presented contingently with the saccade. In the baseline condition (right panel), no preview array was displayed before the saccade. In preview conditions, the presaccadic array was displayed 50 ms after the saccade target onset and remained on until the saccade.

The previewed target was either at the spatiotopic, or retinotopic, or control location relative to its postsaccadic location. To respond, participants reported the position of the small white bar on the pop-out search target (top or bottom). Experiment 2 was identical except that the target and distractors switched colors across the saccade

They answered with the up and down arrows of the keyboard, and response times were recorded. The pop-out target was always present, and its color (red or blue) was not known in advance, changing randomly across trials.

In the no-preview condition used as a baseline, only the postsaccadic search array was presented and no preview was displayed before the saccade as described above. But in the preview conditions, the pop-out array was also displayed just before the saccade, 50 ms after the onset of the target for the saccade; it remained on the screen until the response saccade was detected (on average, the preview was presented for $178 \pm$ (SD) 49 ms, before the saccade started).

The postsaccadic search display consisted of one square of a unique color (red or blue) among ten square distractors of a different color (blue or red; see Figs. 1a and 2). The postsaccadic search target was presented with equal probability at one out of nine potential locations, defined by three vertical eccentricities and three horizontal eccentricities. The pre- and postsaccadic pop-out arrays were identical except for two points: previewed items did not have white bars, and the uniquely colored square could be at different locations in the pre- and postsaccadic arrays (Fig. 2). The unique item in the preview could either match the search target location of the postsaccadic array (spatiotopic condition), or occupy the same retinal location (retinotopic condition), or a control location (control1 referred to the location opposite to the retinotopic

with respect to the spatiotopic location, control2 condition was defined when control1 or retinotopic condition did not exist within the array, see Fig. 1b).

There were four target types (target red or blue, with a small white bar at the top or the bottom), two saccade directions (left or right), and three vertical locations for the search target. These 24 trials types were defined for each of the three horizontal target locations, yielding 72 trials total. For the baseline condition, these 72 trials were distributed randomly in two blocks of 36 trials. The three preview conditions (spatiotopic, retinotopic, and control) were randomly interleaved for a total of 216 trials, distributed in four blocks of 54 trials with short breaks between blocks. Thus, one session had 288 trials. The order of the preview and baseline blocks was counterbalanced across participants and sessions. Each participant completed four sessions for a total of 1,152 trials: two sessions per day with a 15-min break between them. One session lasted approximately 45 min.

Experiment 1. Same-colors preview. The pop-out target and the distractors had the same color assignments in the pre- and postsaccadic displays (e.g., a preview array with a red square among blue distractors was followed by a postsaccadic array with a red square among blue distractors).

Experiment 2. Swapped-colors preview. The unique colored item and the distractors exchanged their color assignments between the preview and the postsaccadic displays

(e.g., a preview array with a red square among blue distractors was followed by a postsaccadic array with a blue square among red distractors).

Analyses

The response saccade was identified online by means of a spatial boundary criterion: it was the first saccade that left a circular region with a radius of 2° around fixation. Onset and offset of the saccade were recorded during the experiment and detected with the default EyeLink criterion defined by eye speed ($30^\circ/\text{s}$) and acceleration ($8,000^\circ/\text{s}^2$). Eye position was recorded from the time of fixation onset to the time of the manual response. We excluded trials according to the following screening criteria: (a) anticipatory saccades (latency < 100 ms), (b) delayed saccades (latency > 800 ms), (c) gaze deviating more than 2° from the fixation dot at the time of the saccade onset, (d) gaze falling closer than 2° to the uniquely colored square at any time. The percentage of rejections is given in the Results section for each experiment.

Saccade latency was defined as the interval between the onset of the saccade target (the signal to make a saccade) and the initiation of the response saccade. Manual reaction times were given by the time difference between the saccade landing and the key press time.

Another criterion excluded trials rerun more than three times because of a persistent incorrect response (for a total of four presentations). To analyze the eccentricity effects in our results, data were grouped at each of the nine potential search target locations in the postsaccadic display (three horizontal $\times$ three vertical). Then the mean at each of the three postsaccadic locations (-17.5° , -7.5° , $+2.5^\circ$) was computed across the vertical locations. The data were merged across saccade directions.

To investigate the effect of the presaccadic singleton presentation on postsaccadic search performance, we ran separate analyses on reaction time and accuracy. Mean reaction time was computed for correct trials only, and mean search accuracy was based only on the first presentation of the trial, but not any reruns. We first established the main effects of the presence of the presaccadic array and target eccentricity by running a 2×3 repeated-measures analysis of variance (ANOVA) on reaction time and search accuracy with preview (with or without) and postsaccadic target eccentricity (-17.5° , or -7.5° , or $+2.5^\circ$) as within-subject factors. We then examined, at each postsaccadic target eccentricity, which spatial reference frame led to a significant preview effect by performing a one-way ANOVA with preview condition as a within-subject factor (three presaccadic singleton locations defining the spatiotopic, retinotopic, and control reference frames and the no-preview baseline), followed by pair-wise corrected t-tests between each preview location and the baseline. We then determined the spatial reference frame of the

preview effect by examining the reaction time and accuracy benefits (difference between the no-preview and preview conditions). To do so, we ran a 3×3 repeated-measures ANOVA with the presaccadic location of the singleton (-7.5° , or $+2.5^\circ$, or $+12.5^\circ$) and the postsaccadic location of the search target (-17.5° , or -7.5° , or $+2.5^\circ$) as within-subject factors. Pair-wise corrected t-tests between the presaccadic locations were performed at each postsaccadic location to compare the preview effect in the various spatial reference frames (spatiotopic, or retinotopic, or control).

Results

Experiment 1: Same-colors preview

Only the trials meeting the screening criteria (see the [Methods](#) section) were included in the analysis. The trials discarded from the analysis represented 2.4% of the total of trials in the no-preview condition and 4.6% in the preview condition. Among these validated trials, the trials with incorrect responses up to the last rerun (error trials were rerun up to a maximum of three times, see the [Methods](#) section) were discarded and represented, respectively for -17.5° , -7.5° , and $+2.5^\circ$ postsaccadic target eccentricity, 20.6%, 2.5%, and 0.5% in the no-preview condition, and 23.9%, 2.0%, and 0.1% in the preview condition. The highest proportion corresponded to the largest eccentricity, where participants frequently reported seeing the white bar on the target inverted (at the bottom when it was at the top and vice versa) and they were confident enough to repeat their incorrect response on all four presentations. We have no explanation for this inversion effect.

Saccade latency (the delay between the saccade cue and the saccade onset) was normal for visually-guided saccades and did not differ between preview and no-preview conditions (respectively $227 \pm (\text{SEM}) 13$ ms, and $221 \pm (\text{SEM}) 16$ ms; $t(7)=1.353$, $p=.218$). Saccade gain (ratio between saccade amplitude and target eccentricity) was also normal, exhibiting the typical undershoot, and did not differ between the preview and no-preview conditions ($0.913 \pm (\text{SEM}) 0.005$ and $0.915 \pm (\text{SEM}) 0.004$ respectively; $t(7)=0.709$, $p=.501$).

Target eccentricity and preview: main effects

Overall, reaction times in the postsaccadic feature search task were faster with a preview ($561 \pm (\text{SEM}) 22$ ms) than without ($595 \pm (\text{SEM}) 25$ ms) [$F(1,7)=16.239$, $p=.005$]. Figure 3a shows mean reaction time as a function of the postsaccadic search target eccentricity, for the conditions with and without preview. In the preview condition, reaction times for each postsaccadic target eccentricity were averaged across spatiotopic, retinotopic, and control locations. The effect of

Fig. 3 Experiment 1. Same-colors preview. (a) Mean reaction time. (b) Mean search accuracy, for the preview (across all presaccadic locations) and no-preview conditions, as functions of postsaccadic target

eccentricity (horizontal component with respect to the direction of the saccade). Error bars indicate $\pm$ within-subjects error

search target eccentricity was also significant [$F(2,14)=39.329$, $p=2E-6$]: performance improved when eccentricity decreased, replicating the classic result in a pop-out feature search task (Carrasco & Katz, 1992), and did so similarly with and without preview, as there was no interaction between the two factors [$F(2,14)=1.569$, $p=.243$].

Overall, search accuracy (Fig. 3b) did not differ between preview and no-preview conditions [respectively $78 \pm$ (SEM) 1% and $79 \pm$ (SEM) 2%; $F(1,7)=2.515$, $p=.157$], but did depend on target eccentricity [$F(2,14)=167.583$, $p=2E-10$]. The greater the eccentricity, the lower the accuracy, in line with previous reports (Meinecke & Donk, 2002). The interaction between the two factors was significant [$F(2,14)=12.431$, $p=.001$]. The preview presentation decreased search accuracy for the farthest eccentricity and increased it slightly for the closest eccentricity [at -17.5° : $t(7)=4.621$, $p=.002$; at -7.5° : $t(7)=-0.793$, $p=.454$, and at $+2.5^\circ$: $t(7)=-2.590$, $p=.036$]. There was no sign of speed-accuracy trade-off for the intermediate and the closest eccentricities, since participants answered faster but without decreasing search accuracy. However, for the farthest target eccentricity, there may be a speed-accuracy trade-off since participants were faster with a preview but also make more mistakes. Consequently, we have discarded the accuracy data at the farthest eccentricity from our interpretation of the results.

Spatial reference frame

Having established that a preview of the pop-out target before the saccade facilitated the postsaccadic search task, we then turned to the spatial reference frame. Overall, the mean reaction time advantage was higher when the previewed singleton and the postsaccadic target occupied the same spatiotopic location ($57 \pm$ (SEM) 11 ms) than when they occupied the same retinotopic location ($27 \pm$ (SEM) 9 ms), or the control location ($19 \pm$ (SEM) 8 ms). These global results are shown in Fig. 4a with the reaction advantage collapsed across eccentricities.

We first examined the preview effect at each postsaccadic eccentricity and in each reference frame. The main effect of preview was significant [at -17.5° : $F(1,3)=5.779$, $p=.005$; at -7.5° : $F(1,3)=10.749$, $p<.001$; and at $+2.5^\circ$: $F(1,3)=21.831$, $p<.001$]. At the farthest postsaccadic target eccentricity, Bonferroni-corrected pair-wise t-tests (significance criterion set at $<.008$) revealed significantly faster reaction times than baseline for the spatiotopic preview location [$t(7)=-3.342$, $p=.006$], but not for the control1 and 2 locations [respectively: $t(7)=-2.080$, $p=.038$; $t(7)=-0.199$, $p=.424$]. At the intermediate postsaccadic target eccentricity, the spatiotopic and control1 but not the retinotopic preview locations significantly decreased response time [respectively: $t(7)=-5.076$, $p<.001$; $t(7)=-5.767$, $p<.001$; $t(7)=-1.341$, $p=.111$]. Finally, for the nearest postsaccadic target, response times were faster for the spatiotopic and retinotopic but not the control2 preview locations [respectively: $t(7)=-3.420$, $p=.006$; $t(7)=-5.896$, $p<.001$; $t(7)=-2.206$, $p=.032$].

Finally, we compared the preview benefit between each reference frame with a repeated-measures ANOVA including presaccadic singleton position (-7.5° , or $+2.5^\circ$, or $+12.5^\circ$) and postsaccadic target location (-17.5° , or -7.5° , or $+2.5^\circ$) as factors, since they defined the spatiotopic, retinotopic, and control conditions (see Fig. 1b). Neither presaccadic nor postsaccadic target location had a significant main effect [$F(2,14)=2.537$, $p=.115$ and $F(2,14)=1.637$, $p=.230$, respectively], but the interaction between the two was significant [$F(4,28)=15.136$, $p=1E-6$] (Fig. 4b).

Bonferroni-corrected pair-wise t-tests (significance criterion set at $<.017$) confirmed that the advantage was maximal for the spatiotopic condition but did not differ between other conditions. At the farthest postsaccadic eccentricity (-17.5°), the reaction time advantage in the spatiotopic condition was not different from the control1 condition [$t(7)=2.327$, $p=.053$], and significantly higher than the control2 condition [$t(7)=3.217$, $p=.015$]. The preview benefit was not statistically different between control1 and control2 conditions [$t(7)=1.799$, $p=.115$]. At the intermediate eccentricity (-7.5°), the reaction time

Fig. 4 Experiment 1. Same-colors preview. **(a)** Overall mean reaction time advantage across all eccentricities. **(b)** Reaction time advantage for each postsaccadic target eccentricity. **(c)** Overall mean search accuracy benefit across all eccentricities. **(d)** Search accuracy benefit for each

postsaccadic target eccentricity. In our design, retinotopic, control1, and control2 conditions could not be tested at every postsaccadic location. Error bars indicate $\pm$ SEM

advantage in the spatiotopic condition was significantly higher compared to the retinotopic condition [$t(7)=-3.842$, $p=.006$] and to the control1 condition [$t(7)=3.465$, $p=.010$]. The benefits for the retinotopic and control1 conditions were not statistically different [$t(7)=-0.981$, $p=.359$]. Finally, at the postsaccadic eccentricity nearest the fovea ($+2.5^\circ$), the reaction time advantage for the spatiotopic condition was significantly higher than the retinotopic condition [$t(7)=-5.330$, $p=.001$] and than the control2 condition [$t(7)=-6.430$, $p=.0004$]. The benefits for the retinotopic and control2 conditions were not statistically different [$t(7)=-2.150$, $p=.069$].

Figure 4c shows the global preview effect on search accuracy across all eccentricities. Overall, the benefit was greatest in the spatiotopic reference frame. Figure 4d shows the preview effect on search accuracy in the various reference frames for each postsaccadic eccentricity. We started by examining the preview effect at each postsaccadic target eccentricity and in each reference frame. The main effect of preview was significant [at -17.5° : $F(1,3)=6.057$, $p=.004$; at -7.5° : $F(1,3)=3.668$, $p=.029$; and at $+2.5^\circ$: $F(1,3)=7.164$, $p=.002$]. At the farthest postsaccadic target eccentricity, Bonferroni-corrected pair-wise t -tests (significance criterion set at $<.008$) revealed that search accuracy was significantly lower than the baseline for the control1 and control2 preview locations

[respectively: $t(7)=-3.834$, $p=.003$; $t(7)=-3.949$, $p=.003$], but not for the spatiotopic location [$t(7)=-1.565$, $p=.081$]. At the intermediate postsaccadic target eccentricity, neither the spatiotopic, retinotopic or control1 preview locations led to a significant effect on search accuracy [respectively: $t(7)=2.597$, $p=.018$; $t(7)=-0.296$, $p=.612$; $t(7)=0.034$, $p=.487$]. Finally, for the nearest postsaccadic target, search accuracy improved with the preview of the spatiotopic but not of the retinotopic and control2 locations [respectively: $t(7)=5.337$, $p<.001$; $t(7)=1.682$, $p=.068$; $t(7)=-0.561$, $p=.704$].

The search accuracy benefit had a pattern close to that of the reaction time advantage, except at the farthest eccentricity where we observed the decrease in accuracy (plotted as a negative value in Figs. 4c and d). As noted above, a speed-accuracy trade-off may be present at -17.5° , or the target could be too far in the periphery to benefit from the preview. An ANOVA confirmed that, contrary to the outcome with reaction times, the effect of postsaccadic eccentricity on search accuracy was significant [$F(2,14)=12.793$, $p=.001$]. In line with the reaction time advantage analysis, the presaccadic singleton location that defined the reference frame did not have any impact on search accuracy [$F(2,14)=0.128$, $p=.881$] and the interaction between pre- and postsaccadic target eccentricity was significant [$F(4,28)=6.038$, $p=.001$].

We examined the accuracy differences between the spatiotopic, retinotopic, and control reference frames at each postsaccadic target eccentricity by performing repeated-measures ANOVAs with the presaccadic singleton position (-7.5° , or $+2.5^\circ$, or $+12.5^\circ$) as a factor (see Fig. 1b). Search accuracy benefit was significantly impacted at the intermediate and the nearest eccentricities [at -17.5° : $F(2,14)=2.940$, $p=.086$; at -7.5° : $F(2,14)=6.954$, $p=.008$, and at $+2.5^\circ$: $F(2,14)=7.265$, $p=.007$]. For the farthest eccentricity, the cost on accuracy was not statistically different in the various reference frames [$F(2,14)=2.940$, $p=.086$]. Pair-wise t-tests (Bonferroni-corrected with a significance criterion set at $<.017$) showed that at the intermediate eccentricity (-7.5°), the search accuracy benefit in the spatiotopic condition was significantly higher than the retinotopic [$t(7)=4.683$, $p=.002$] but not than the control1 condition [$t(7)=2.493$, $p=.041$]. The benefits for the retinotopic and control1 conditions were not statistically different [$t(7)=0.392$, $p=.707$]. At the postsaccadic eccentricity nearest the fovea ($+2.5^\circ$), the search accuracy benefit for the spatiotopic condition was significantly higher than the control2 condition [$t(7)=4.044$, $p=.005$] but not than the retinotopic condition [$t(7)=2.636$, $p=.034$]. The benefit for the retinotopic and control2 conditions were not statistically different [$t(7)=1.268$, $p=.245$].

To sum up Experiment 1, the results showed that the preview of the pop-out array improved performance in the postsaccadic search task: participants were faster and more accurate. The preview benefit on reaction times was greatest in the spatiotopic reference frame compared to the retinotopic and control locations. This reference frame effect was not due to eccentricity because the mean postsaccadic target eccentricity was smaller in the retinotopic (-2.5°) than in the spatiotopic condition (-7.5°), but nevertheless, the mean preview benefit was higher in the spatiotopic reference frame.

Experiment 2: Swapped-colors preview

In the second experiment, we examined whether the preview benefit acted through spatial attention or feature-based attention, or both. To do this, the colors of the target and distractors were exchanged during the saccade, so the colors in the postsaccadic array were swapped compared to the presaccadic array. We asked whether there would be a spatial attentional advantage at the singleton location regardless of the color change, or whether the advantage would be specific to the previewed color.

Trials were discarded from the analysis according to the screening criteria (see the [Methods](#) section). These represented 3.9% of the total of trials in the no-preview condition and 4.4% in the preview condition. Among the validated trials, the proportions of trials with a persistent incorrect answer (see the [Methods](#) section) for -17.5° , -7.5° , and $+2.5^\circ$ postsaccadic target eccentricity were respectively 21.5%, 1.5%, and 0.7%

in the no-preview condition, and 27.5%, 5.4%, and 3.2% in the preview condition. As for Experiment 1, the highest proportion corresponded to the largest eccentricity, where participants frequently and inexplicably reported that the location of the white bar on the target was inverted.

In Experiment 2 with swapped colors for target and distractors across the saccade, the presaccadic presentation impacted saccade latencies, with longer latencies with ($230 \pm$ (SEM) 21 ms) than without a preview ($213 \pm$ (SEM) 18 ms) [$t(7)=3.570$, $p=.017$]. The eccentricity of the presaccadic singleton did not influence saccade latencies [$F(2,14)=3.570$, $p=.056$].

Target eccentricity and preview: main effects

Overall, participants responded more slowly with a swapped-colors preview ($631 \pm$ (SEM) 30 ms) than without ($596 \pm$ (SEM) 31 ms) [$F(1,7)=98.266$, $p=2E-5$]. Figure 5a shows mean reaction times for the preview (reaction times were averaged across spatiotopic, retinotopic, and control locations) and no-preview conditions as a function of postsaccadic search target eccentricity. The search target eccentricity was also significant [$F(2,14)=15.290$, $p=3E-4$]. Search performance improved when eccentricity decreased, replicating both the classic result in a pop-out feature search task (Carrasco & Katz, 1992) and Experiment 1. In contrast to Experiment 1, the interaction between the preview and postsaccadic eccentricity factors was significant [$F(2,14)=5.483$, $p=.017$]. The preview did not slow response times similarly at each search target eccentricity. Pair-wise t-tests revealed that the preview effect was significant only for the intermediate and for the closest eccentricities [at -17.5° : $t(7)=1.387$, $p=.208$; at -7.5° : $t(7)=6.444$, $p=4E-4$; at $+2.5^\circ$: $t(7)=10.383$, $p=2E-5$]. This interaction will be further analyzed according to the previewed singleton locations that define the different spatial reference frames for a given postsaccadic location.

Overall, search accuracy was significantly lower in the preview compared to the no-preview condition [$80 \pm$ (SEM) 1% vs. $72 \pm$ (SEM) 2%; $F(1,7)=25.659$, $p=.001$], the opposite of the result in Experiment 1 with the same-colors preview. Search accuracy also depended on target eccentricity [$F(2,14)=88.052$, $p=2E-8$] (Fig. 5b) (Meinecke & Donk, 2002) as for Experiment 1, but the interaction between the two factors was not significant [$F(2,14)=1.116$, $p=.355$]. Thus, a preview of the pop-out with swapped colors reduced search accuracy at all postsaccadic eccentricities. There was no sign of a speed-accuracy trade-off. Participants were slower with a preview and did not make fewer errors.

Spatial reference frame

The postsaccadic search performance was impaired by the swapped-colors preview and we then examined this effect

Fig. 5 Experiment 2. Swapped-colors preview. (a) Mean reaction times. (b) Mean accuracies, for the preview (across all presaccadic locations) and no-preview conditions, as functions of postsaccadic target

eccentricity (horizontal component with respect to the direction of the saccade). Error bars indicate $\pm$ within-subjects error

for the various reference frames. Overall, participants' responses were slowed by the preview the least at the spatiotopic location ($-18 \pm$ (SEM) 6 ms) compared to other locations (retinotopic: $-54 \pm$ (SEM) 5 ms; control: $-41 \pm$ (SEM) 4 ms). Figure 6a shows these global costs, collapsed across all eccentricities and plotted as negative values.

The preview effect on reaction time was first examined at each postsaccadic target eccentricity and in each reference frame. The main effect of preview was significant for the intermediate and nearest target eccentricities [at -17.5° : $F(1,3)=1.800$, $p=.178$; at -7.5° : $F(1,3)=11.170$, $p<.001$; at $+2.5^\circ$: $F(1,3)=39.880$, $p<.001$]. At the intermediate

postsaccadic target eccentricity, Bonferroni-corrected pairwise t-tests (significance criterion set at $<.008$) revealed that response time was significantly slower than baseline for the retinotopic and control1 preview locations [$t(7)=6.423$, $p<.001$; $t(7)=5.157$, $p<.001$] but not for the spatiotopic location [$t(7)=3.033$, $p=.010$]. For the nearest postsaccadic target, the spatiotopic, retinotopic and control2 preview locations all showed significantly increased response time [$t(7)=4.071$, $p=.002$; $t(7)=9.161$, $p<.001$; $t(7)=8.200$, $p<.001$].

The next ANOVA confirmed the difference in reaction time cost between the reference frames with the previewed singleton location as a factor [$F(2,14)=5.814$, $p=.015$], and showed as

Fig. 6 Experiment 2. Swapped-colors preview. (a) Overall mean reaction time cost across all eccentricities. (b) Reaction time cost for each postsaccadic eccentricity. (c) Overall mean search accuracy cost across all eccentricities. (d) Search accuracy cost for each postsaccadic target

eccentricity. In our design, retinotopic, control1 and control2 conditions could not be tested at every postsaccadic location. Error bars indicate $\pm$ SEM

well the impact of postsaccadic target eccentricity [$F(2,14)=5.507$, $p=.017$]. The interaction between these two factors also significantly affected reaction time costs [$F(4,28)=12.195$, $p=7E-6$]. The impact of the presaccadic location was significant only for the target nearest the fovea (Fig. 6b) [at -17.5° : $F(2,14)=1.116$, $p=.355$; at -7.5° : $F(2,14)=3.013$, $p=.082$, and at $+2.5^\circ$: $F(2,14)=22.524$, $p=4E-5$]. At the $+2.5^\circ$ postsaccadic location, Bonferroni-corrected pair-wise t-tests (significance criterion set at $<.017$) revealed that the reaction time cost was significantly lower in the spatiotopic condition than the retinotopic condition [$t(7)=5.685$, $p=.001$] and than the control2 condition [$t(7)=4.554$, $p=.003$]. The cost preview for the retinotopic and control2 conditions were not statistically different [$t(7)=0.780$, $p=.461$].

The overall cost on search accuracy across all eccentricities is plotted as negative values in Fig. 6c and was least for the spatiotopic condition ($-5 \pm$ (SEM) 1%) compared to other locations (retinotopic: $-8 \pm$ (SEM) 1%; control: $-10 \pm$ (SEM) 2%). We examined the preview effect at each postsaccadic target eccentricity and in each reference frame. The main effect of preview was significant [at -17.5° : $F(1,3)=4.729$, $p=.011$; at -7.5° : $F(1,3)=4.154$, $p=.019$; at $+2.5^\circ$: $F(1,3)=16.284$, $p<.001$]. At the farthest postsaccadic target eccentricity, Bonferroni-corrected pair-wise t-tests (significance criterion set at $<.008$) revealed significantly lower search accuracy than baseline for the control1 preview location [$t(7)=-5.534$, $p<.001$], but not for the spatiotopic and control2 locations [respectively: $t(7)=-2.103$, $p=.037$; $t(7)=-1.739$, $p=.063$]. At the intermediate postsaccadic target eccentricity, neither spatiotopic, retinotopic or control1 preview locations had a significant effect on search accuracy [respectively: $t(7)=-2.735$, $p=.015$; $t(7)=-1.921$, $p=.048$; $t(7)=-2.762$, $p=.014$]. Finally, for the nearest postsaccadic target, search accuracy was impaired at the retinotopic and control2 preview locations [respectively: $t(7)=-5.528$, $p<.001$; $t(7)=-6.890$, $p<.001$] but not at the spatiotopic location [$t(7)=-2.590$, $p=.018$].

As opposed to reaction time cost, the ANOVA on search accuracy cost did not reveal any global effect of the postsaccadic target eccentricity [$F(2,14)=1.027$, $p=.383$] or of the presaccadic singleton location that defined the various reference frames [$F(2,14)=1.116$, $p=.355$]. But as for the reaction time cost, the interaction between the two factors was significant [$F(4,28)=4.862$, $p=.004$]. One-way ANOVAs showed that the presaccadic location had an impact only at the nearest eccentricity [at -17.5° : $F(2,14)=1.939$, $p=.181$; at -7.5° : $F(2,14)=1.969$, $p=.176$, and at $+2.5^\circ$: $F(2,14)=7.933$, $p=.005$]. At $+2.5^\circ$ eccentricity, pair-wise corrected (significance criterion set at $<.017$) t-tests revealed that the search accuracy cost in the spatiotopic condition was significantly lower than the control2 condition [$t(7)=4.193$, $p=.004$] but not than the retinotopic condition [$t(7)=2.980$, $p=.021$]. The costs for the retinotopic and control1 conditions were not statistically different [$t(7)=0.638$, $p=.544$].

To sum up Experiment 2, the results showed that the swapped-colors preview impaired search performance. With a preview in which target and distractors had reversed colors, participants were slower and less accurate at all locations, showing that the previewed features were selected and impacted the search performance after the saccade. At the $+2.5^\circ$ postsaccadic target eccentricity, the mean cost of the preview was the least in the spatiotopic reference frame compared to the retinotopic and control reference frames, replicating the spatial advantage found in Experiment 1. This location-specific advantage was present whether or not the color switched, but the color switch added a large cost to all locations.

Discussion

In this study we examined the interplay between saccades and feature-based attention to better understand the role of feature-based attention in matching pre- to postsaccadic visual information. We assessed the transsaccadic processing of a pop-out target, where feature-based attention guides spatial attention to the target location. Participants performed a pop-out search task on a peripheral array presented right after the saccade landed. We asked whether search performance was modulated by a similar array previewed just before the saccade, in which the color singleton could either be at the same spatiotopic location, or at another location (retinotopic or control).

In Experiment 1 the color assignments of target and distractors remained identical across the saccade and previewing the singleton facilitated search performance with faster reaction times in the postsaccadic task. This preview effect was greatest in the spatiotopic condition, i.e., when the previewed singleton and the postsaccadic target occupied the same location in space. When they occupied the same location on the retina, there was no reaction time benefit relative to control conditions. These results suggest that in the previewed pop-out array, features were processed across the visual field and (1) the singleton attracted attention to its location, (2) this location was remapped across the saccade to maintain the same position in space, and (3) there was no residual benefit at the retinal location. The absence of a residual retinotopic benefit is in line with studies on spatial priming of pop-out (Tower-Richard et al., 2016). Furthermore, studies that reported a retinotopic advantage across the saccade examined spatial attention for locations defined and known in advance (e.g., Jonikaitis et al., 2013), which was not the case here. Finally, it is possible that the retinotopic effect is much smaller than the spatiotopic effect due to the spatial references in our display (Golomb, Pulido, Albrecht, Chun, & Mazer, 2010; Lisi, Cavanagh, & Zorzi, 2015), and as a result our design simply failed to detect it.

We suggest that the remapping of the singleton location caused the spatiotopic advantage but there is an alternative explanation. The position of spatial attention across the saccade could take place in both world-centered and object-centered reference frames; these were confounded in our design. Consistent with this idea, strong positional priming across trials occurs in both world- and object-centered reference frames in color pop-out search tasks (Gokce et al., 2015; Tower-Richardi et al., 2016). Furthermore, in a study without saccades, Theeuwes and colleagues reported a strong spatial cueing effect in both the retinotopic and the object-centered reference frames, supporting that spatial and object-centered systems can coexist for the exogenous orientation of attention (Theeuwes, Mathôt, & Grainger, 2013).

In Experiment 2, when the color of target and distractors were swapped across the saccade, previewing the singleton just before the saccade impaired postsaccadic search performance: whatever the location of the color singleton before or after the saccade, the preview always led to slower reaction times and lower accuracy in the postsaccadic task. The global benefits and costs with the same-colors and swapped-colors previews revealed the transfer of feature information across the saccade: the pop-out array colors had been selected during the preview and passed to processing after the saccade. Our results show that the preview effect not only guided spatial attention to the pop-out target location, but also extracted the target and distractor colors. This suggests that feature-based attention also plays a role across the saccade, having set the values of the target and distractor colors. When these are reversed, processing is set back.

Our results contrast with traditional feature search tasks without saccades. Previous work on classical priming of pop-out (i.e., when repeating the target and distractor colors improves performance, without eye movements) showed that a passive preview – without a search task – does not produce feature priming (Goolsby & Suzuki, 2001; Kristjánsson, Saevarsson, & Driver, 2013). However, in our experimental procedure, we found a feature-based effect even though there was no explicit task on the brief preview (the white marks were not yet present). However, the comparison between our study and classical feature search tasks without saccade remains limited since the previous studies tested inter-trial priming as opposed to transsaccadic priming within a trial. Nevertheless, Kalogeropoulou and Rolfs (2017) showed recently that the deployment of feature-based attention is continuous and not disrupted by saccades. According to this recent finding, the color switch in our experiment would have impacted performance similarly with or without eye movements, at least at the time scale of the presentations of our two arrays.

Importantly, the cost of the swapped colors preview was least at the spatiotopic location, and comparable between retinotopic and control locations. Clearly the guidance of

spatial attention from the previewed target was preserved and its location remapped despite the color switch. As a result, any stimulus falling at the remapped location should have benefited from improved processing. This indicates a spatial preview effect that maintains a spatiotopic locus of attention across the saccade independently of feature processing, in line with models of remapping (Cavanagh, Hunt, Afraz, & Rolfs, 2010; Wurtz, 2008). We suggest that the preview effects result from the combination of the spatiotopic transfer of the attentional locus and a spatially independent correspondence of the target and distractor colors between the previewed and postsaccadic arrays. The priming effects of previewed features and location would be additive to maximize benefit in the same-colors experiment, and work in opposite directions to minimize cost in the swapped-colors experiment. Such spatial and feature-based preview effects would be independent, at least partly, and extend a recent finding that singletons attract spatial attention independently of feature priming (Yashar, White, Fang, & Carrasco, 2017) to include conditions of transsaccadic processing.

The parallel between our study and the classical priming of pop-out (without eye movements) remains limited by the temporal scale difference of the search array repetition. Nevertheless, it is interesting to compare our results to those of classical priming of pop-out. Classical studies with reaction time tasks sometimes found a dependence between feature and location priming (Campana & Casco, 2009; A. Treisman, Vieira, & Hayes, 1992), and sometimes independence (Maljkovic & Nakayama, 1996). Ásgeirsson and collaborators (2014) attributed the differences in these findings to post-perceptual response-related processes when the search array is displayed until response. They used a brief display presentation (~70 ms) to rule out those processes and focus on perceptual attentional mechanisms. In these conditions, they found that spatial and color repetitions have independent priming effects on accuracy (Ásgeirsson, Kristjánsson, & Bundesen, 2014). In our procedure, the postsaccadic search array was also briefly presented (~50 ms) and we observed a priming effect on accuracy that suggests independent effects of previewed features and location.

In these experiments we asked whether feature-based attention plays a role in visual stability. Visual stability is achieved when the information of an attended object – its visual identity, location, and the link between them – are maintained across the saccade and matched with postsaccadic information. Our results showed that both features and location of a pop-out target were transferred across the saccade, and that spatiotopy was established regardless of the previewed colors. This suggests that for a pop-out target the feature-based preview effect may play no role in maintaining the spatiotopy of the locus of attention. A recent study on transsaccadic processing tested object correspondence, although only at the spatiotopic location, and showed that

performance in an identification task relies on the previewed color (Poth & Schneider, 2016). This could suggest that feature-based selective processes may be dedicated to object correspondence, and future studies could consider whether it would be possible to maintain the visual identity, or the link between an object and its location, or both.

To sum up, our results show that both feature-based and spatial processing took place during the presentation of the preview array and that both of these affected the postsaccadic search. The spatiotopic effect observed on search performance, regardless of the previewed colors, suggests independent priming effects of features and location. Taken together, our results favor a dissociation between feature-based attention and the attentional mechanism associated with eye movements.

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References

- Ásgeirsson, Á. G., Kristjánsson, Á., & Bundesen, C. (2014). Independent priming of location and color in identification of briefly presented letters. *Attention, Perception, & Psychophysics*, 76(1), 40–48. <https://doi.org/10.3758/s13414-013-0546-6>
- Becker, S. I., Valuch, C., & Ansorge, U. (2014). Color priming in pop-out search depends on the relative color of the target. *Frontiers in Psychology*, 5. <https://doi.org/10.3389/fpsyg.2014.00289>
- Brainard, D. (1997). The Psychophysics Toolbox. *Spatial Vision*, 433–436. <https://doi.org/10.1163/156856897x00357>
- Bravo, M. J., & Nakayama, K. (1992). The role of attention in different visual-search tasks. *Perception & Psychophysics*, 51(5), 465–472. <https://doi.org/10.3758/BF03211642>
- Campana, G., & Casco, C. (2009). Repetition effects of features and spatial position: Evidence for dissociable mechanisms. *Spatial Vision*, 22(4), 325–338. <https://doi.org/10.1163/156856809788746318>
- Carrasco, M., & Katz, S. M. (1992). The effect of target position in a feature visual search task. *Paper presented at the 63rd Annual Meeting of the Eastern Psychology Association, Boston, MA*.
- Castet, E., Jeanjean, S., Montagnini, A., Laugier, D., & Masson, G. S. (2006). Dynamics of attentional deployment during saccadic programming. *Journal of Vision*, 6, 196–212.
- Cavanagh, P., Hunt, A. R., Afraz, A., & Rolfs, M. (2010). Visual stability based on remapping of attention pointers. *Trends in Cognitive Sciences*, 14(4), 147–153. <https://doi.org/10.1016/j.tics.2010.01.007>
- Cornelissen, F. W., Peters, E. M., & Palmer, J. (2002). The Eyelink Toolbox: Eye tracking with MATLAB and the Psychophysics Toolbox. *Behavior Research Methods, Instruments, & Computers*, 34(4), 613–617. <https://doi.org/10.3758/BF03195489>
- Eimer, M., Kiss, M., & Cheung, T. (2010). Priming of pop-out modulates attentional target selection in visual search: Behavioural and electrophysiological evidence. *Vision Research*, 50(14), 1353–1361. <https://doi.org/10.1016/j.visres.2009.11.001>
- Eymond, C., Cavanagh, P., & Collins, T. (2016). Feature-based attention across saccades and immediate post-saccadic selection. *Attention, Perception & Psychophysics*, 78(5), 1293–1301. <https://doi.org/10.3758/s13414-016-1110-y>
- Gokce, A., Müller, H. J., & Geyer, T. (2015). Positional priming of visual pop-out search is supported by multiple spatial reference frames. *Frontiers in Psychology*, 6. <https://doi.org/10.3389/fpsyg.2015.00838>
- Golomb, J. D., Pulido, V. Z., Albrecht, A. R., Chun, M. M., & Mazer, J. A. (2010). Robustness of the retinotopic attentional trace after eye movements. *Journal of Vision*, 10(3), 19.1–12. <https://doi.org/10.1167/10.3.19>
- Goolsby, B. A., & Suzuki, S. (2001). Understanding priming of color-singleton search: Roles of attention at encoding and « retrieval ». *Perception & Psychophysics*, 63(6), 929–944. <https://doi.org/10.3758/BF03194513>
- Jonikaitis, D., Szinte, M., Rolfs, M., & Cavanagh, P. (2013). Allocation of attention across saccades. *Journal of Neurophysiology*, 109(5), 1425–1434. <https://doi.org/10.1152/jn.00656.2012>
- Jonikaitis, D., & Theeuwes, J. (2013). Dissociating oculomotor contributions to spatial and feature-based selection. *Journal of Neurophysiology*, <https://doi.org/10.1152/jn.00275.2013>
- Kalogeropoulou, Z., & Rolfs, M. (2017). Saccadic eye movements do not disrupt the deployment of feature-based attention. *Journal of Vision*, 17(8), 4. <https://doi.org/10.1167/17.8.4>
- Kleiner, M., Brainard, D., Pelli, D., Ingling, A., Murray, R., & Broussard, C. (2007). What's new in psyctoolbox-3. *Perception*, 36(14). Consulté à l'adresse <https://nyuscholars.nyu.edu/en/publications/whats-new-in-psyctoolbox-3>
- Kristjánsson, Á., Saevarsson, S., & Driver, J. (2013). The boundary conditions of priming of visual search: From passive viewing through task-relevant working memory load. *Psychonomic Bulletin & Review*, 20(3), 514–521. <https://doi.org/10.3758/s13423-013-0375-6>
- Lisi, M., Cavanagh, P., & Zorzi, M. (2015). Spatial constancy of attention across eye movements is mediated by the presence of visual objects. *Attention, Perception, & Psychophysics*, 77(4), 1159–1169. <https://doi.org/10.3758/s13414-015-0861-1>
- Maljkovic, V., & Nakayama, K. (1994). Priming of pop-out: I. Role of features. *Memory & Cognition*, 22(6), 657–672. <https://doi.org/10.3758/BF03209251>
- Maljkovic, V., & Nakayama, K. (1996). Priming of pop-out: II. The role of position. *Perception & Psychophysics*, 58(7), 977–991. <https://doi.org/10.3758/BF03206826>
- Mathôt, S., & Theeuwes, J. (2010). Gradual Remapping Results in Early Retinotopic and Late Spatiotopic Inhibition of Return. *Psychological Science*, 21(12), 1793–1798. <https://doi.org/10.1177/0956797610388813>
- Meinecke, C., & Donk, M. (2002). Detection Performance in Pop-Out Tasks: Nonmonotonic Changes with Display Size and Eccentricity. *Perception*, 31(5), 591–602. <https://doi.org/10.1068/p3201>
- Montagnini, A., & Castet, E. (2007). Spatiotemporal dynamics of visual attention during saccade preparation: Independence and coupling between attention and movement planning. *Journal of Vision*, 7(14), 8.1–16. <https://doi.org/10.1167/7.14.8>
- Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision*, 10(4), 437–442.
- Poth, C. H., & Schneider, W. X. (2016). Breaking object correspondence across saccades impairs object recognition: The role of color and luminance. *Journal of Vision*, 16(11), 1–12. <https://doi.org/10.1167/16.11.1>
- Rolfs, M., Jonikaitis, D., Deubel, H., & Cavanagh, P. (2011). Predictive remapping of attention across eye movements. *Nature Neuroscience*, 14(2), 252–256. <https://doi.org/10.1038/nn.2711>
- Theeuwes, J. (2010). Top-down and bottom-up control of visual selection. *Acta Psychologica*, 135(2), 77–99. <https://doi.org/10.1016/j.actpsy.2010.02.006>
- Theeuwes, J., Mathôt, S., & Grainger, J. (2013). Exogenous object-centered attention. *Attention, Perception, & Psychophysics*, 75(5), 812–818. <https://doi.org/10.3758/s13414-013-0459-4>

- Tower-Richardi, S. M., Leber, A. B., & Golomb, J. D. (2016). Spatial priming in ecologically relevant reference frames. *Attention, Perception, & Psychophysics*, 78(1), 114–132. <https://doi.org/10.3758/s13414-015-1002-6>
- Treisman, A., Vieira, A., & Hayes, A. (1992). Automaticity and preattentive processing. *The American Journal of Psychology*, 105(2), 341–362.
- Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, 12(1), 97–136. [https://doi.org/10.1016/0010-0285\(80\)90005-5](https://doi.org/10.1016/0010-0285(80)90005-5)
- White, A. L., Rolfs, M., & Carrasco, M. (2013). Adaptive deployment of spatial and feature-based attention before saccades. *Vision Research*, 85, 26–35. <https://doi.org/10.1016/j.visres.2012.10.017>
- Wurtz, R. H. (2008). Neuronal mechanisms of visual stability. *Vision Research*, 48(20), 2070–2089. <https://doi.org/10.1016/j.visres.2008.03.021>
- Yashar, A., White, A. L., Fang, W., & Carrasco, M. (2017). Feature singletons attract spatial attention independently of feature priming. *Journal of Vision*, 17(9), 7–7. <https://doi.org/10.1167/17.9.7>