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Impact of dynamic bottom-up features and top-down control on the visual exploration of moving real-world scenes in hemispatial neglect

Björn Machner [a,*], Michael Dorr [b,c], Andreas Sprenger [a], Janina von der Gablentz [a], Wolfgang Heide [d], Erhardt Barth [c], Christoph Helmchen [a]

[a] *Dept. of Neurology, University of Lübeck, Lübeck, Germany*
[b] *Schepens Eye Research Institute, Massachusetts Eye and Ear Infirmary, Dept. of Ophthalmology, Harvard Medical School, Boston, MA, USA*
[c] *Institute for Neuro- and Bioinformatics, University of Lübeck, Lübeck, Germany*
[d] *General Hospital Celle, Celle, Germany*

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ABSTRACT

Patients with hemispatial neglect are severely impaired in orienting their attention to contralesional hemispace. Although motion is one of the strongest attentional cues in humans, it is still unknown how neglect patients visually explore their moving real-world environment.

We therefore recorded eye movements at bedside in 19 patients with hemispatial neglect following acute right hemisphere stroke, 14 right-brain damaged patients without neglect and 21 healthy control subjects. Videos of naturalistic real-world scenes were presented first in a free viewing condition together with static images, and subsequently in a visual search condition. We analyzed number and amplitude of saccades, fixation durations and horizontal fixation distributions. Novel computational tools allowed us to assess the impact of different scene features (static and dynamic contrast, colour, brightness) on patients' gaze.

Independent of the different stimulus conditions, neglect patients showed decreased numbers of fixations in contralesional hemispace (ipsilesional fixation bias) and increased fixation durations in ipsilesional hemispace (disengagement deficit). However, in videos left-hemifield fixations of neglect patients landed on regions with particularly high dynamic contrast. Furthermore, dynamic scenes with few salient objects led to a significant reduction of the pathological ipsilesional fixation bias. In visual search, moving targets in the neglected hemifield were more frequently detected than stationary ones. The top-down influence (search instruction) could neither reduce the ipsilesional fixation bias nor the impact of bottom-up features.

Our results provide evidence for a strong impact of dynamic bottom-up features on neglect patients' scanning behaviour. They support the neglect model of an attentional priority map in the brain being imbalanced towards ipsilesional hemispace, which can be counterbalanced by strong contralateral motion cues. Taking into account the lack of top-down control in neglect patients, bottom-up stimulation with moving real-world stimuli may be a promising candidate for future neglect rehabilitation schemes.

1. Introduction

Hemispatial neglect is a common and disabling cognitive disorder in patients who suffered a stroke (Bowen, McKenna, & Tallis, 1999; Parton, Malhotra, & Husain, 2004). Typically, damage to the right hemisphere is associated with this severe deficit of spatial attention (Verdon, Schwartz, Lovblad, Hauert, & Vuilleumier, 2010), particularly if cortical areas around the temporo-parietal junction (Mort et al., 2003), perisylvian regions (Karnath, Fruhmann, Kuker, & Rorden, 2004) or parietal-frontal white matter tracts are affected (Doricchi, Thiebaut de Schotten, Tomaiuolo, & Bartolomeo, 2008).

Patients with left spatial neglect fail to respond to stimuli in the left visual hemifield and almost never spontaneously orient to their contralesional hemispace (Parton et al., 2004). Reduced exogenous capture of visual attention in the contralesional hemifield is one crucial aspect in hemispatial neglect, as is the impairment of endogenous 'allocation' of visual attention towards the contralesional hemifield (Mort & Kennard, 2003). It is known that very strong attentional cues in contralesional space are able to overcome the neglect syndrome to a certain degree (Riddoch & Humphreys, 1983). However, little is known about neglect behaviour and its interference with one of the strongest cues for selective attention in humans (Wolfe & Horowitz, 2004), i.e., *motion*.

* Correspondence to:Department of Neurology, University of Lübeck, Ratzeburger Allee 160, D-23538 Lübeck, Germany. Tel.: +49 451 5003709; fax: +49 451 5002489.
E-mail address: Bjoern.Machner@neuro.uni-luebeck.de (B. Machner).

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In healthy subjects, motion has been shown to attract the eyes even more than colour, intensity or orientation (Itti, 2005), most probably because the human visual system evolved in an environment where fast reactions to dynamic visual cues were biologically extremely relevant. Previous studies in neglect patients indicated that dynamic cues are possibly able to modulate the extent of neglect behaviour. For example, task-irrelevant kinetic stimuli on the left margin of a visual search display increased the detection rate of left-sided single target letters among distractors (Butter & Kirsch, 1995). Related studies used single moving targets but without distractors (Dunai, Bennett, Fotiades, Kritikos, & Castiello, 1999), abstract displays with dynamic random dot noise (Braun, Petersen, Schonle, & Fahle, 1998; Vaina, Cowey, Eskew, Jr., LeMay, & Kemper, 2001) or optokinetic background stimulation during a basic visuo-motor task (line bisection) (Pizzamiglio, Frasca, Guariglia, Incoccia, & Antonucci, 1990; Mattingley, Bradshaw, & Bradshaw, 1994; Plummer, Dunai, & Morris, 2006). Given the integrity of motion-relevant cortical areas (e.g., V5) in neglect patients, most of the studies were principally in favour of a beneficial effect of motion. However, the visual real-world environment exceeds by far the attentional demands of previous experimental settings and usually lacks artificial motion cues. Furthermore, little is known about neglect patients' perception of higher-order biological motion (Battelli et al., 2001; Battelli, Cavanagh, & Thornton, 2003), and to our knowledge, no previous study has tested moving real-world stimuli in neglect patients.

By recording eye movements in neglect patients and control subjects, we investigated the impact of *local motion* (dynamic contrast) and other bottom-up features during free scanning of dynamic and static real-world scenes as well as the influence of top-down control (task instruction) during visual search. First, in the free viewing condition, stimulus-driven scanning behaviour was compared between dynamic videos and static images. Second, the visual search condition was introduced to elicit task-driven (top-down controlled) visual exploration of dynamic scenes.

We hypothesized that the global ipsilesional shift of attention (and eye fixations) in neglect patients would be reduced due to an alerting effect (Robertson, Mattingley, Rorden, & Driver, 1998) of the moving scenes. Consequently, we expected regions of relatively high dynamic contrast to especially attract patients' gaze and even to draw their attention into contralesional hemispace. Finally, we assumed that introducing a search task would not only suppress the influence of bottom-up features and yield top-down driven scanning patterns in neglect patients, but that it would also reveal a higher chance for *moving* real-world targets to be detected than for *stationary* ones.

2. Subjects and methods

2.1. Participants

The experiment was approved by the ethics committee of the University of Lübeck (no. 07–053). After obtaining informed written consent, 54 subjects participated in this study: 19 patients with left hemispatial neglect following right-hemisphere stroke ("neglect patients"), 21 healthy control subjects ("controls") and 14 patients with acute right-hemisphere brain damage, but without any signs of hemispatial neglect ("RBD"). The patients were in-patients of the Department of Neurology/University Hospital Schleswig-Holstein, Campus Lübeck. All participants had a (corrected) visual acuity above 0.7.

The three study groups did not differ with respect to their mean age (see Table 1 for neglect patients and RBDs, controls' mean age 69 years ± 9) and neglect patients and RBDs were comparable regarding the time passed since stroke onset.

First-time ever right-hemisphere stroke was confirmed by magnetic resonance imaging (MRI). Patients with multiple brain lesions were excluded from the study. Lesions were mapped on normalized brain scans and further analyzed (Machner, Sprenger, Hansen, Heide, and Helmchen, 2009a) using the free imaging software MRICro (http://www.cabiatl.com/mricro) for lesion overlaps and MRICron for VLSM, the voxel-wise lesion-symptom mapping (Rorden & Brett, 2000; Mort et al., 2003; Rorden, Karnath, & Bonilha, 2007).

Table 1
Clinical characteristics and paper-and-pencil test performance in neglect patients and right brain-damaged patients without neglect (*RBD*).

	Neglect	RBD
Demographic and clinical data		
Patients (n)	19	14
Age (years)	70 ± 14	63 ± 19
Sex (% male)	53	21
Time passed since stroke (days)	8 ± 6	6 ± 3
NIH-Stroke Scale ($_{max.}$ 42)	10 ± 5	3 ± 2
Visual field defects (%)	33	0
Eye/head deviation ($_{max.}$ 3)	1.5 ± 0.8	0.2 ± 0.4
Paper-and-pencil tests		
Mesulam cancellation		
Omissions (total, max. 60)	33 ± 20	5 ± 5
Omissions (left minus right)	6 ± 5	1 ± 3
Starting point (% right)	93	31
Star cancellation		
Omissions (total, max. 54)	26 ± 19	2 ± 3
Omissions (left minus right)	6 ± 8	0 ± 2
Starting point (% right)	95	0
Line bisection (20 cm)		
Deviation from centre (%)	34 ± 28	0 ± 6
Figure copying (Ogden scene)		
Omissions ($_{max.}$ 4)	3 ± 1	0 ± 1
Reading		
Word omissions ($_{max.}$ 140)	65 ± 52	0

Mean ± SD.

2.2. Assessment of spatial neglect—Clinical examination and paper–pencil tests

Patients were assigned to the neglect group if they showed clinical signs of spatial neglect (e.g., inattention to objects or persons in left hemispace) in a screening bedside examination and additionally pathological test results in at least two of the standard paper-and-pencil tests as described below. As no single test alone is able to diagnose the multi-modal neglect syndrome in all patients (Parton et al., 2004), we used a combination of different tests in order to increase the sensitivity and specificity for detecting hemispatial neglect (Azouvi et al., 2002; Gottesman et al., 2008). The following paper-and-pencil tests were presented at bedside on an A4 horizontal sheet of paper:

Cancellation tasks: subjects were asked to cross out 56 small stars presented among 65 distractors in the star cancellation task (Wilson, Cockburn, & Halligan, 1987), and 60 target objects among over 300 distractors in Mesulam and Weintraub's cancellation task, respectively (Mesulam, 1985). The number of total omissions and the difference between left and right hemifield omissions were counted. The cut-off (left minus right omissions) was set at >2 omissions (Azouvi et al., 2002). Additionally, we registered the subject's starting point (left or right side of the sheet).

Figure copying: subjects were asked to copy the Ogden scene, i.e., drawing a tree, a fence, a house and a second tree (Ogden, 1985). The five level scale ranged from 0 (no omissions) to 4 (omission of one left sided object and at least one left part of another object).

Line bisection: participants were instructed to mark the centre of 3 lines of 20 cm length (Schenkenberg, Bradford, & Ajax, 1980; Machner et al., 2009b). The cut-off was set at >6.5 mm deviation from the centre (Azouvi et al., 2006).

Oral reading: subjects were asked to read a text containing 140 words, displayed in three separate columns (Wilson et al., 1987). The cut-off was set at >1 omission.

Furthermore, patients were clinically examined for associated disorders such as visual extinction, visual field defects, spontaneous gaze and head deviation. Finally, patients were assessed with standardized measures of disability following stroke including the NIH Stroke Scale (NIHSS) and the Barthel-Index for the functional assessment of activities of daily living (Mahoney & Barthel, 1965).

2.3. Experimental procedure

Eye movement recordings were performed at bedside. This allowed inclusion of patients suffering from acute stroke without discontinuing their monitoring and treatment on the stroke unit. Participants were seated comfortably with the head stabilized in front of a 24" widescreen TFT monitor (Samsung SyncMaster 2443BW with a resolution of 1920 × 1200 pixel and a refresh rate of 60 Hz). At an eye-to-screen distance of 60 cm the display covered a visual field of 48° × 30°.

Stimuli comprised 18 naturalistic scenes (Fig. 1) from the city of Lübeck and surrounding area (Dorr, Martinetz, Gegenfurtner, & Barth, 2010), each being displayed for 20 s and always following the same order. In the first block, scenes were presented as either *dynamic* video clips ($n=8$) or as *static* images, i.e., snapshots from the videos ($n=4$) that had been randomly inserted between the movie trials. Participants were asked to attentively watch the scenes with no specific task given (''free viewing condition'').

In the subsequent ''visual search condition'', only videos ($n=6$) were presented and participants were asked to search for a pre-defined target within the dynamic scene. Before each trial, the target instruction was given by reading out loud the target's name, which was additionally shown in white capital letters on a black screen. Targets represented naturalistic objects within the scenes (e.g., wheelchair, bus), that were located either on the left or right half of the screen and were either moving or stationary ($n=3$ for each side and mode). Upon detection of the target, participants were instructed to press a response button.

Eye movements were recorded throughout the experiment using a contact-free remote eye tracker running at 50 Hz (RED-X, SensoMotoricInstruments, Teltow, Germany). A 13-point calibration at the beginning was supported by additional drift corrections before each trial. In case of neglecting the calibration points on the contralesional side, patients were verbally instructed or – if necessary – manually guided to the calibration points.

2.4. Statistics and data analysis

Eye movement data were individually screened and fixation and saccades were manually corrected by an interactive program written in Matlab® (R2010b, The Mathworks, Natick MA). Due to the 50 Hz sampling rate of the eye tracker we recorded fixations and between-fixation-intervals. These intervals were defined as *saccades* if there was a change in the position of 2 consecutive samples of $>0.5°$ visual angle and if the latter gaze position was stable over at least 60 ms.

Statistical analyses of eye movement data were performed using the SPSS software package (PASW 18.0.3, IBM Corporation, Somer NY). The study design with 3 different study groups (neglect patients, control subjects and RBDs) and 3 stimulus conditions (free viewing – movies, free viewing – images, and visual search) required 3 × 3 ANOVAs with repeated measures. Post-hoc tests including a Bonferroni correction assessed significant differences (d) between groups. Data in the text are given in mean ± standard error of mean unless stated differently.

2.5. Computation of local scene features at fixation

In order to evaluate the impact of different local scene features on gaze position, we basically performed three steps of analysis. First, we chose and defined different physical scene properties that are known to attract gaze in humans, i.e., salient scene features. Second, for each subject in each image and video frame we computed the intensity of these features at currently fixated parts of a scene. Third, the results of the feature intensity at fixation were smoothed and averaged for each study group and were graphically displayed as a function of horizontal screen position. Finally, an additional function was computed and displayed for virtual fixations randomly distributed over the screen, which allows comparison of the group results to a ''baseline'' that takes a potential imbalance of feature content across the scene into account.

The above mentioned steps will now be described in more detail. First, the following scene features were chosen for analysis: *brightness*, *colour*, *static contrast*, and *dynamic contrast*. Out of the images and video frames that were visually explored by the participants, we extracted image patches of 3° × 3° of visual angle centered on saccadic landing points. Then we computed the mean intensity of the features in each patch. For the feature brightness, we used the luminance information (Y′ channel of the Y′CbCr colour space) that was contained in the MPEG-encoded video streams and JPEG-encoded still images. For the feature colour, we first converted stimuli to the perceptually equidistant Lab colour space and then computed the vector length of its colour channels. Our computation of *static* and *dynamic contrast* was based on an eigenvalue analysis of the structure tensor, which is a standard technique in image processing (Jähne, 1999). To put it simple, in a homogeneous image region (e.g., blue sky) the rank of the spatial structure tensor is zero (because all eigenvalues are zero). At edges the rank of the spatial structure tensor is one, and at corners it is two. For the *static contrast* measure *H*2, we extracted all the regions containing edges and corners from every image or video frame. Thus, *H*2 practically corresponds to the 2-dimensional spatial structure of a scene. For the dynamic contrast measure *K*, we extracted regions of spatio-temporal change (3 dimensions), i.e., *K* practically corresponds to corners of moving objects. Our choice of *H*2 and *K* was motivated by the fact that these measures are embedded in a framework that unifies spatial and temporal dimensions and that they have proven useful in describing various biological phenomena (Zetzsche, Barth, & Wegmann, 1993). The measure *K* has also been used successfully in predicting eye movements (Vig, Dorr, Martinetz, & Barth, 2012).

However, the spatial distribution of all these features in natural scenes is not uniform. And various parts of a scene containing intense features may have been fixated only by chance. In order to disambiguate this phenomenon from space-variant selection biases of the subjects, we repeated the above analysis for a set of randomly sampled locations for each stimulus, using the same number of fixations as in the control group. This basically reflects virtual fixations spread all over the screen landing on different parts of the scene that contain a certain intensity of each feature.

Finally, all the extracted features within 1° of horizontal screen position were averaged for each group and smoothed using a local polynomial function. We therefore applied the standard ''loess'' function of the *R* statistical software (http://www.r-project.org), using default parameters. Data were re-sampled and loess-fitted 5000 times and 95% confidence intervals are reported.

3. Results

3.1. Lesion analyses

In Fig. 2a and b, lesion overlaps are shown separately for neglect patients and RBDs, i.e., right-brain damaged patients without neglect. The average lesion volume was significantly larger in neglect patients (113.0 cm^3 ± 23.6 cm^3) than in RBDs (44.8 cm^3 ± 15.8 cm^3, *t*-test, $T=2.2$, $p=0.034$). Using the sensitive Liebermeister measure (Rorden et al., 2007), statistical voxel-wise lesion-symptom mapping (VLSM) was conducted to identify

Fig. 1. Stimuli. Representative examples of naturalistic scenes from Lübeck and the surrounding area used as static (images) or dynamic (videos) visual stimuli (coloured).

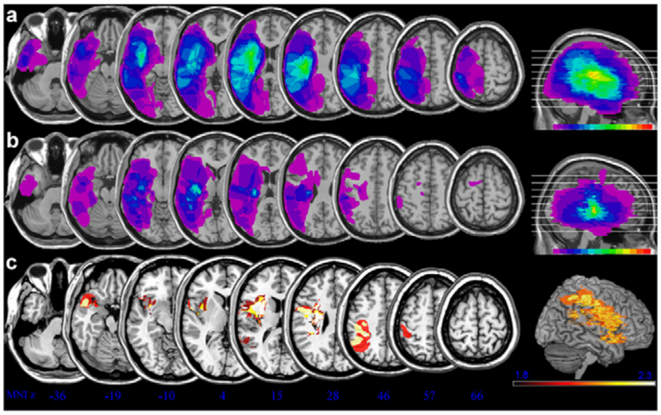

Fig. 2. Lesion overlaps and voxel-wise lesion-symptom mapping (VLSM). Lesion overlaps are shown for neglect patients (a) and RBDs, right-brain damaged patients without neglect, (b) Montreal Neurological Institute (MNI) *z* coordinates of each transverse section are given beneath. The lesions of both patient groups were further statistically compared on a voxel-wise basis, (c) only voxels significant at $p<0.05$ (false discovery rate corrected) are shown colour-coded, with the colour range indicating *z*-values from the VLSM analysis. The brain areas that were more frequently affected in neglect patients (**c**) were the anterior part of the superior temporal gyrus (slice -19), the insula and rolandic operculum (slices 4 and 15), subcortical centro-parietal white matter (slice 28) as well as the inferior parietal lobule (slice 46). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

voxels that are significantly more frequently involved in neglect patients than in RBDs (Fig. 2c).

Lesions in our neglect patients predominantly involved anterior parts of the superior temporal gyrus (MNI coordinates: $46\times13\times-19$), perisylvian areas including the insula ($38\times8\times4$) and the fronto-parietal operculum ($42\times2\times15$), an area within the centro-parietal white matter ($26\times-10\times28$) as well as the inferior parietal lobule ($40\times-48\times46$).

3.2. Saccade parameters

Means of saccade parameters are presented in Table 2, separately for each study group and the different stimulus conditions (free viewing of static vs. dynamic scenes, and visual search).

For the parameter *number of saccades*, only trials from the free viewing condition were analysed (always 20 s duration), because trials from the search condition varied in terms of duration (and also number of saccades) depending on when the target detection button was pressed. The 3×2 ANOVA revealed a main effect only for "group" ($F(2,51)=23.0$, $p<0.001$) and post-hoc tests showed a reduced number of saccades in neglect patients when compared to controls ($d=-14.4\pm2.4$, $p<0.001$) and RBDs ($d=14.9\pm2.7$, $p<0.001$).

Analyses were performed for *left hemifield saccades (% of total)*, i.e., the percentage of all saccades landing in the absolute left hemifield, as well as for *leftward saccades (% of total)*, i.e., the percentage of all saccades directed towards the left. These analyses using relative values included also the trials from the search condition. In the 3×3 ANOVA on *left hemifield saccades* there were significant main effects for the factors "group" ($F(2,50)=73.1$, $p<0.001$), "task" ($F(2,50)=4.4$, $p=0.01$) and "group*task" ($F(4,100)=6.9$, $p=0.002$). Post-hoc tests showed markedly reduced percentages of left hemifield saccades in neglect patients as compared to controls ($d=-28.4\%\pm2.4$, $p<0.001$) and RBDs ($d=-23.7\%\pm2.7$, $p<0.001$). Within-group analyses revealed that the task had an influence only in controls showing less left hemifield saccades (%) in the search condition than in the free viewing condition of static and dynamic scenes ($p=0.001$; Table 2).

Table 2
Saccade parameters of neglect patients, control subjects and right brain damaged subjects without neglect (RBD) separately for the different stimulus conditions.

	Neglect			Controls			RBD		
	Images—Free viewing	Movies—Free viewing	Movies—Visual search[a]	Images—Free viewing	Movies—Free viewing	Movies—Visual search[a]	Images—Free viewing	Movies—Free viewing	Movies—Visual search[a]
Saccades, *n*	17 (2)	18 (1)	15 (1)	32 (2)	32 (2)	11 (1)	33 (3)	31 (2)	14 (2)
left hemifield [%]	19 (3)	23 (2)	24 (3)	55 (2)	55 (2)	45 (3)	50 (3)	46 (3)	43 (3)
leftward [%]	53 (2)	55 (2)	52 (3)	52 (1)	51 (1)	47 (2)	50 (2)	51 (2)	46 (2)
Amplitude [°]	4.9 (.4)	5.8 (.4)	5.8 (.4)	7.2 (.4)	7.8 (.4)	8.0 (.5)	7.1 (.4)	7.4 (.3)	8.1 (.6)
left hemifield	4.4 (.7)	6.4 (.8)	6.3 (.6)	7.4 (.4)	7.8 (.4)	8.1 (.5)	7.5 (.5)	8.2 (.4)	8.4 (.7)
right hemifield	4.9 (.4)	5.8 (.3)	5.9 (.5)	7.6 (.5)	8.1 (.3)	9.1 (.6)	6.8 (.4)	7.3 (.4)	8.1(.5)
leftward saccades	5.2 (.4)	6.1 (.4)	6.1 (.4)	7.4 (.5)	7.7 (.4)	7.9 (.5)	7.1 (.5)	7.5 (.4)	8.2 (.7)
rightward saccades	4.3 (.5)	5.5 (.5)	5.7 (.5)	7.3 (.4)	8.1 (.4)	8.8 (.6)	7.2 (.3)	7.6 (.3)	8.2 (.5)
Fixation duration [ms]	623 (59)	745 (87)	621 (67)	412 (29)	444 (28)	475 (37)	375 (22)	400 (25)	481 (40)
left hemifield	362 (40)	543 (80)	480 (49)	407 (30)	447 (31)	411 (33)	363 (23)	380 (23)	446 (61)
right hemifield	650 (66)	779 (91)	665 (84)	419 (34)	444 (30)	487 (48)	370 (29)	410 (28)	472 (40)

Means (dark grey) $\pm$ sem (light grey).
[a] Saccades and fixations analyzed until the target response button was pressed.

The 3×3 ANOVA on *leftward saccades (% of total)* revealed no significant main effects for "group" or "task".

For the parameter *saccade amplitude* we performed two different analyses. The first analysis took into account the *hemifield* (left vs. right) in which the saccade finally landed. The second analysis investigated the influence of the *saccade direction* (leftward vs. rightward) on the saccade amplitude.

In the $3 \times 3 \times 2$ ANOVA (group $\times$ task $\times$ hemifield) on *saccade amplitude* there was a main effect for "group" ($F(2,50)=9.3$, $p<0.001$) and "task" $F(2,49)=18.5$, $p<0.001$), but no main effect or significant interaction for the factor "hemifield". Post-hoc tests for the factor group revealed significantly smaller saccade amplitudes in neglect patients than in controls ($d=-2.4^\circ \pm 0.6$, $p<0.001$) and RBDs ($-2.1^\circ \pm 0.6$, $p=0.006$). Post-hoc tests for the factor task revealed smaller saccade amplitudes during free viewing of images than during free viewing of videos ($-0.8^\circ \pm 0.2$, $p<0.001$) and than in the search condition ($-1.2^\circ \pm 0.2$, $p<0.01$).

In the $3 \times 3 \times 2$ ANOVA (group $\times$ task $\times$ saccade direction) on *saccade amplitude* there were again main effects for the factors "group" ($F(2,50)=10.8$, $p<0.001$) and "task" ($F(2,49)=21.5$, $p<0.001$) and additionally an interaction of "group∗saccade direction" $F(2,50)=5.0$, $p=0.011$). Subsequent ANOVAs separately for each group revealed that there was a significant main effect for the factor "saccade direction" only in the neglect group ($F(1,53)=15.6$, $p=0.011$) with leftward saccades being slightly larger than rightward saccades ($d=0.6 \pm 0.2$). Further ANOVAs performed for each saccade direction separately revealed significant main effects for the group (leftward saccades: $F(2,53)=6.7$, $p=0.003$, rightward saccades: $F(2,52)=16.3$, $p<0.001$), with smaller amplitudes of both leftward ($d=-1.9^\circ \pm 0.6$, $p=0.005$) and rightward saccades ($d=-3.0 \pm 0.6$, $p<0.001$) in neglect patients as compared to control subjects.

For the analysis of *single fixation duration* we performed a $3 \times 3 \times 2$ ANOVA, including the factors group, task and hemifield. This revealed main effects for "group" ($F(2,50)=6.9$, $p<0.01$), "task" ($F(2,49)=10.1$, $p<0.001$), "hemifield" ($F(1,50)=13.0$, $p<0.01$) and an interaction of "hemifield∗group" ($F(2,50)=7.2$, $p<0,01$).

Post-hoc tests for the factor "group" showed a higher mean fixation duration in neglect patients than in controls ($d=148$ ms $\pm$ 48, $p=0.01$) and RBDs ($d=177$ ms $\pm$ 54, $p=0.005$). Post-hoc tests for the factor "task" revealed decreased mean fixation durations in static images as compared to free viewing in movies (-74 ms $\pm$ 21 ms) and the search task (-64 ms $\pm$ 22 ms). Post-hoc tests for the factor "hemifield" showed a significantly higher mean fixation duration in the right than in the left hemifield ($d=93$ ms $\pm$ 26, $p=0.01$).

Investigating the interaction of "hemifield∗group" further, subsequent one-way ANOVAs separately for each group revealed a main effect for the factor "hemifield" only in the neglect group ($F(1,17)=10.7$, $p<0.01$). Post-hoc tests showed that neglect patients′ fixation durations in the right hemifield lasted longer than fixations in the left hemifield ($d=230$ ms $\pm$ 70, $p=0.004$).

3.3. Horizontal fixation distribution

Horizontal fixation distributions were analysed for each group and condition by relating mean fixation frequency (%) to horizontal location (°) on the stimulus screen (Fig. 3a). Negative values corresponded to left hemifield fixations ($_{max.}$ -24°), positive values to right hemifield fixations ($_{max.}$ $+24^\circ$), while 0° denominated the screen centre. Neglect patients usually fixated the right half of the screen and almost never explored the furthermost left. This led to an overall restricted field of exploration. The peak of fixation, i.e., the median horizontal position of all

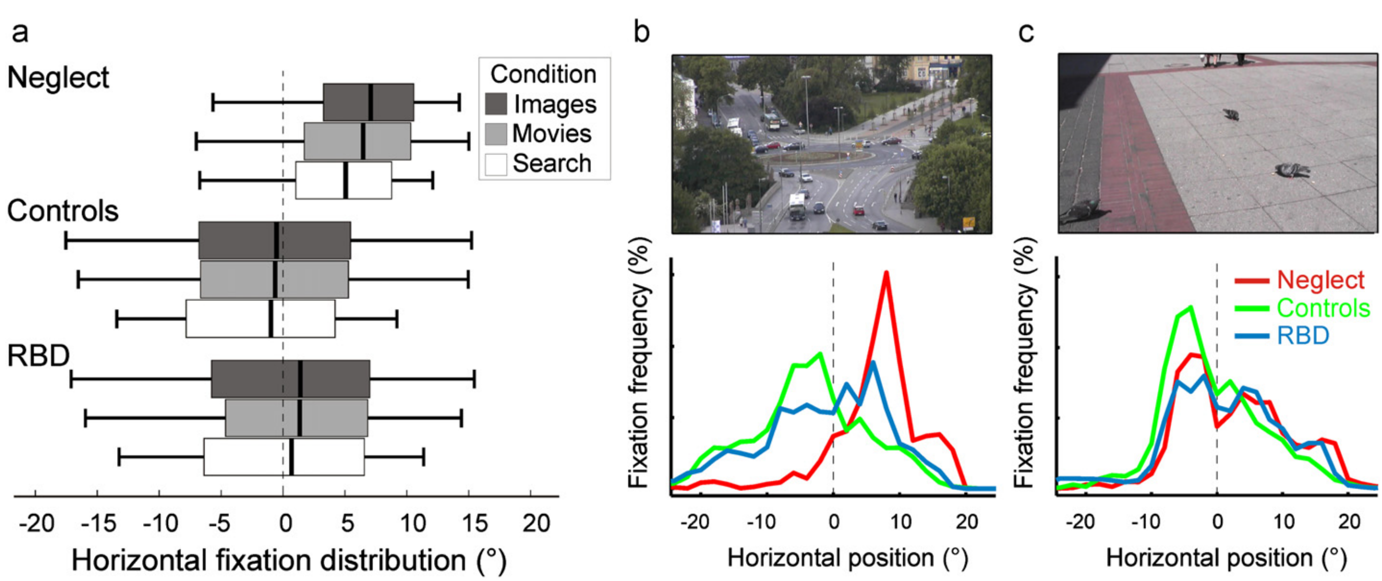

Fig. 3. Horizontal fixation distribution: (a) the *horizontal fixation distribution* is illustrated as a boxplot function of fixation frequency in relation to horizontal fixation location (°) on the screen. Means are shown from the three study groups (neglect patients, control subjects and the "RBD" subjects, i.e., right-brain damaged subjects without neglect), separately for the three stimulus conditions (free viewing of images and movies, visual search). Boxes represent the 25th to 75th percentile including the median band (*peak of fixation*), while ends of the whiskers show minima and maxima, i.e., the averaged limits of the field of exploration. Please note that the *peak of fixation* is clearly deviated to the right side in neglect patients and that their overall *field of exploration* is markedly restricted. In (b) and (c) still shots out of two dynamic video scenes are shown (upper row), together with the mean horizontal fixation distributions from the three study groups in each of those scenes (lower row). In the complex "roundabout" video scene (b), neglect patients fixated almost exclusively the right half of the screen, whereas fixations of controls and RBDs were widely distributed over the whole scene. During the sparse "pigeons" video scene (c), neglect patients explored further to the left and almost identically to healthy controls, possibly related to the relative lack of salient stimuli in the right half of the scene. Please find additional e-videos of both scenes with superimposed eye movement samples from neglect patients (red squares) and healthy control subjects (black squares) as online supplement (See Appendix A). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

fixations, was markedly deviated to the right in neglect patients, while being slightly left of the centre in healthy controls and slightly right of the centre in RBDs (Fig. 3a).

Accordingly, in the 3×3 ANOVA there was a main effect of "group" on *peak of fixation* ($F(2,50)=46.5$, $p<0.001$) and a mild but significant effect of "task" on peak of fixation ($F(2,49)=4.5$, $p=0.016$), but no interaction of "group*task".

Post-hoc tests for the factor "group" revealed significant differences ($p<0.001$) between neglect patients (mean$=6.0^\circ \pm 0.5$) and controls ($-0.9^\circ \pm 0.5$) and RBDs ($0.9^\circ \pm 0.6$), respectively. Post-hoc tests for the factor task showed that the search condition led to a mild leftward shift of the peak of fixation (mean$=1.3^\circ \pm 0.4$) as compared to the free viewing conditions (images $2.5^\circ \pm 0.4$, videos $2.2^\circ \pm 0.4$).

When analyzing neglect patients' fixation distributions on a single trial base, differences between individual scenes became apparent (Fig. 3b and c, see also supplemental e-videos). In contrast to the common rightward bias in most of the trials (Fig. 3b), the dynamic "pigeons" scene with few informative, centrally located, moving objects on a sparse background led to horizontal fixation distributions in neglect patients that were almost identical to those of healthy controls (Fig. 3c). A similar attenuation of the pathological strong rightward shift of fixations in neglect patients was also observed in a sparse static scene ("boats on the sea", see Fig. 1, centre row, right column).

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.neuropsychologia.2012.06.012.

3.4. Impact of local scene features on fixation

Local scene feature analyses were performed for different physical scene properties (brightness, colour, static contrast and dynamic contrast; see also Section 2). Fig. 4 shows the feature intensities at fixated regions depicted as a function of horizontal screen position, separately for the three experimental conditions and the different study groups.

3.4.1. Videos—Free viewing condition

For static contrast $H2$ in the video—free viewing condition (Fig. 4a, upper row, first column), healthy controls showed a strong bias for higher contrast intensities as compared to random fixations. RBD subjects fixated regions of similar strong static contrast as controls in the centre and left half of the screen but tended to regions with lower static contrast in the right half. Neglect patients were less driven by static contrast than controls across the whole visual field, however, their fixations were still preferring regions with higher saliency than expected by chance.

For dynamic contrast K (second row, first column), which roughly reflects the intensity of local motion, healthy controls again showed a clear bias towards higher feature intensities as compared to random fixations. RBD subjects fixated regions of similar dynamic contrast as controls, except for the far right end of the screen, where fixations landed on regions of lower dynamic contrast.

In neglect patients there was an interesting dissociation of their response to dynamic contrast between different parts of the scenes (Fig. 4a, first column, second row). That was especially apparent when taking their horizontal fixation distributions (Fig. 4b) into account, in particular their main field of exploration and peak of fixation (see also Fig. 5 for detailed information).

To the right of their peak of fixation, neglect patients fixated areas of low dynamic contrast which was close to the random fixation function and significantly lower than in controls. Conversely, left of their peak of fixation, neglect patients fixated parts of very high dynamic contrast, even significantly higher than in controls.

For the features colour (Fig. 4a, bottom row) and brightness (third row), fixations from all study groups did not prefer regions of especially high intensities, when compared to random fixations (green curve). Thus, both features had no significant impact on the gaze position of the participants.

3.4.2. Images—Free viewing condition

In images, the intensity of static contrast was much higher at control and RBD fixations than at random fixations, with no difference between the two groups (Fig. 4, centre column, first row). Across the entire visual field, fixations of neglect patients landed on regions of higher static contrast than expected by random fixations, but still of lower contrast intensities than in controls and RBDs. For brightness (Fig. 4, centre column, third row) there was a tendency to lower feature intensities (i.e., darker areas) in all study groups. The features colour had no significant influence on fixations in all three study groups (Fig. 4, centre column, bottom row).

3.4.3. Videos—Visual search condition

In the search condition (Fig. 4, third column), fixations of both healthy controls and RBDs went to parts of the scene, that had lower static contrast than expected by chance (green random curve), whereas fixations from neglect patients still preferred regions of higher static contrast. For the feature dynamic contrast, healthy controls and RBDs showed a bias towards highly dynamic events only at the centre of the screen; fixations at the periphery landed on regions of lower dynamic contrast than with the random fixation function. While neglect patients fixated regions of similar dynamic intensities as controls in the left hemifield, they fixated regions of relatively higher dynamic contrast than controls, RBDs and random fixations in the right hemifield. In all study groups, there was preference for lower intensities of the feature brightness, i.e., dark areas that may have contained search-relevant objects. The analysis of the feature colour did not reveal a uniform impact on fixation and there was almost no significant difference between the three study groups (apart from the areas at the far left end of the screen).

3.5. Target detection rate in visual search trials

A $3 \times 2 \times 2$ ANOVA (3 groups: neglect patients, RBD and controls; 2 target kinetics: stationary, moving; 2 target locations on the screen: left hemifield, right hemifield) was performed for the *target detection rate* (%), i.e., the percentage of trials where the target was found by the subjects and indicated by a button press (Fig. 6). There were significant main effects for the factors "group" ($F(2,49)=30.4$; $p<0.001$) and "target location" ($F(1,49)=18.7$; $p<0.001$) as well as for the interaction between "group*target location" ($F(2,49)=27.4$; $p<0.001$) and "group*target location*target kinetics" ($F(2,49)=4.8$; $p=0.01$). Post-hoc analyses revealed that the *target detection rate* was lower in neglect patients than in controls ($d=-44.3\% \pm 5.8$, $p<0.001$) and RBDs ($d=35.9\% \pm 6.5$; $p<0.001$). In neglect patients, targets located on the left side of the screen were less likely to be found than targets on the right side ($d=39.7\% \pm 7.7$, $p<0.001$). However, on the "neglected" left side of the screen, moving targets were more frequently detected than stationary ones ($d=35.3\% \pm 11.9$, $p<0.01$; Fig. 4).

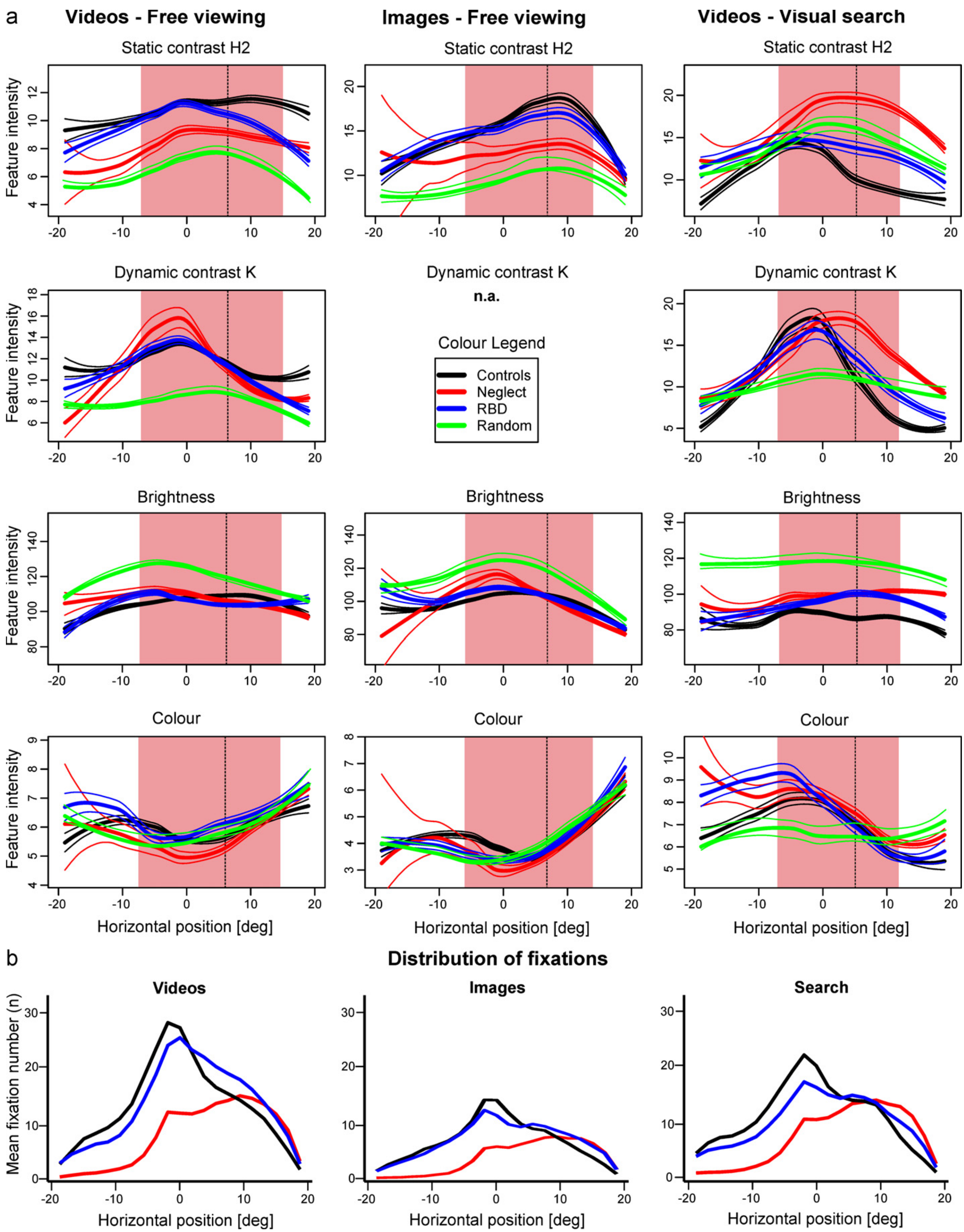

Fig. 4. Intensities of local scene features at fixation: (a) for brightness, colour, static contrast and dynamic contrast, the feature intensities at fixated regions are illustrated as a function of horizontal screen position, separately for the three experimental conditions and the different study groups including a random fixation function. Thick lines represent the mean of each study group, thin lines the 95% confidence interval. The highlighted area in light red represents the main field of exploration of the neglect patient group, the dashed line shows their peak of fixation. For further explanation please be referred to the main text (result section, paragraph 3.4), (b) the graphs at the bottom of the panel show fixation distribution histograms for each study group and condition, i.e., mean number of fixations in relation to the *x*-position on the screen. Therefore each patient's fixations within bins (columns) of 2° across the whole screen were summed and averaged for each condition. The finally displayed group means were smoothed using a Gaussian filter. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

This study investigated the impact of bottom-up features as well as top-down control during visual exploration of moving real-world scenes in patients with hemispatial neglect following stroke. Main results were that, during spontaneous scanning of moving scenes, neglect patients′ fixations were attracted by regions of especially high dynamic contrast in the neglected hemifield. Furthermore, during visual search in naturalistic moving scenes, target detection was facilitated when the target was moving. However, despite the influence of dynamic bottom-up features, the general rightward fixation bias of neglect patients was not reduced compared to stationary scenes, and top-down control during visual search in videos was too weak to overcome this bias either.

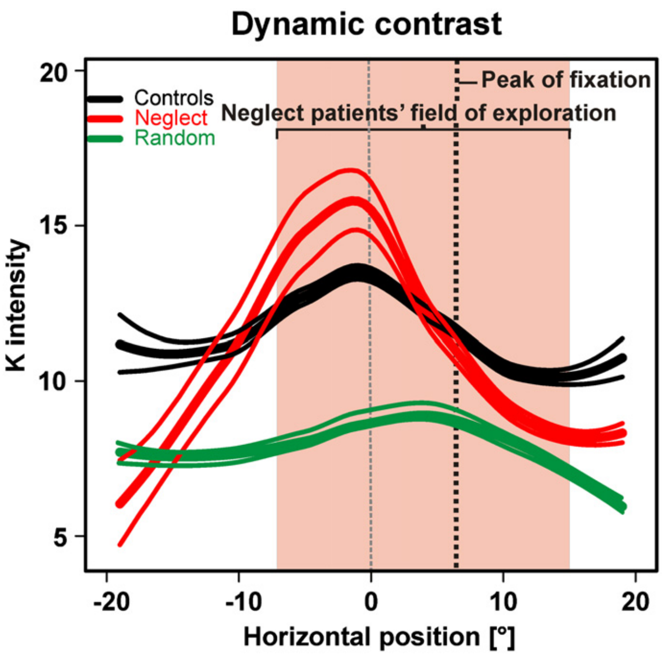

Fig. 5. The intensity of dynamic contrast at fixation in relation to fixation distribution of neglect patients during the free viewing of videos. The intensity of *dynamic contrast K* at fixation (*y*-axis) as a function of horizontal screen position (*x*-axis) is shown together with the field of exploration (light red area) of neglect patients in the movies—free viewing condition. Thick lines represent the means for the control group (black), neglect patients (red) and random fixations (green), thin lines show the 95% confidence interval. The RBD group is omitted here for clarity purposes. In neglect patients, the intensity of *dynamic contrast* at fixation varied in relation to the horizontal position of their fixations. Fixated parts of the video lying right-hand of neglect patients' peak of fixation (dashed line) had very low dynamic contrast intensities, close to those of random fixations and significantly lower than in controls. In contrast, the fixated parts lying left of their peak of fixation contained very high dynamic contrast, much higher than in controls. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The study cohort was representative for neglect patients with patients showing moderate to severe spatial neglect in clinical bedside examination as well as in standardized paper-and-pencil tests. Their acute brain lesions involved cortical structures that have been suggested to be crucial for the neglect syndrome: parts of the superior temporal gyrus, the perisylvian region and the inferior parietal lobe (Mort et al., 2003; Karnath et al., 2004; Verdon et al., 2010). Furthermore subcortical centro-parietal white matter damage was significantly associated with the neglect syndrome in our patients. This hotspot is located within parietal-frontal white matter tracts matching the superior longitudinal fasciculus (SLF II), a pathway subserving spatial attention in humans (Thiebaut de Schotten et al., 2005). Previous studies which also found this area to be associated with hemispatial neglect discussed a disconnection of these parietal-frontal white matter tracts as a major cause of the neglect syndrome (Doricchi & Tomaiuolo, 2003; Committeri et al., 2007; He et al., 2007; Doricchi et al., 2008). According to these data, neglect patients of our study are comparable to previous studies in terms of clinical features as well as anatomical lesion patterns.

In the first part of the experiment we focussed on the impact of dynamic bottom-up features, since local motion cues are biologically most relevant in real-world visual scenes and they are known to be extremely powerful in capturing human attention. Using eye movement recordings, we compared patients′ scanning patterns in moving real-world scenes (videos) to those in stationary scenes (images). Furthermore, we investigated the intensity of different low level features at fixation. Finally, by introducing a search task, we assessed the impact of top-down control on exploratory eye movements in dynamic scenes and looked for a potential benefit of moving targets.

4.1. Free viewing of dynamic and static naturalistic scenes

As compared to the control groups, neglect patients had a lower number of overall fixations, smaller saccadic amplitudes and a clear imbalance between the two hemifields with only about 20% of all fixations landing in the left (neglected) hemifield.

In line with Ptak and colleagues (Ptak, Golay, Müri, & Schnider, 2009) the overall reduction of saccadic amplitude in neglect patients was irrespective of saccade direction, thus both ipsilesional and contralesional saccades were smaller than in control

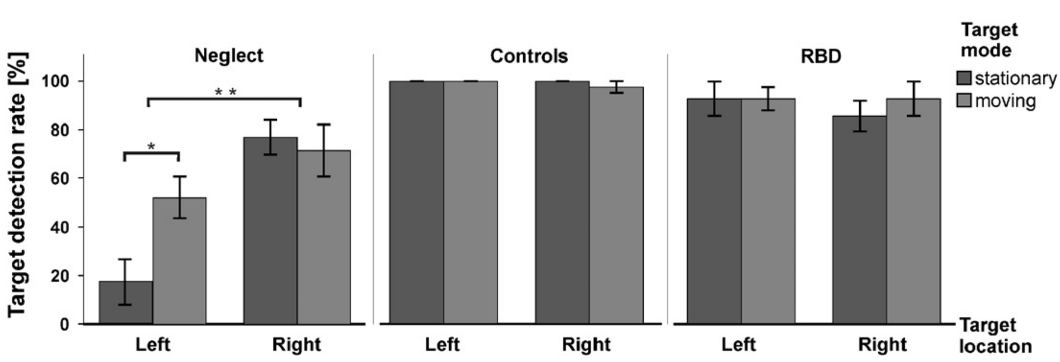

Fig. 6. Target detection rate. The *target detection rate* (%) denominates the percentage of search trials where the participants found the target and responded with a button press. Target detection rates are shown for each study group and further separated based on the target location (left or right hemifield) and mode (stationary or moving). Neglect patients found overall less targets than healthy controls and RBDs. Targets located on the left side of the screen were less often found by neglect patients than targets on the right side. Interestingly, moving targets were more frequently detected than stationary ones within the "neglected" left hemifield.

subjects. This may be due to the restricted field of exploration during a free scanning paradigm as opposed to basic saccade paradigms, where neglect patients exhibit normal ipsilesional reflexive saccades to single salient targets (Heide & Kömpf, 1998).

For our neglect patients, there was no significant impact of the different stimulus conditions (videos vs. images) on global fixation distributions and basic saccade parameters. Specifically, the number of left hemifield saccades in neglect patients did not increase when presenting videos as compared to images. Neither did the ipsilesionally deviated peak of fixations normalize nor did the field of exploration expand when neglect patients watched dynamic videos. This contradicts one of our hypotheses, that the patients' pathological rightward shift of exploratory eye movements would be reduced when watching the more alerting moving scenes.

However, independent of the stimulus condition, there was an influence of the hemifield on the fixation duration in neglect patients. Single fixation durations lasted longer in the right hemifield than in the neglected left hemifield. This may indicate a deficit of neglect patients to disengage from ipsilesional stimuli while watching naturalistic scenes. Hence, the presentation of moving images did not alter this fundamental component of the neglect syndrome.

Independent of whether the scene was moving or not, global analyses of fixation distributions revealed, that the load of information within a scene co-determined the severity of neglect scanning behaviour. In scenes with a low number of salient objects and only little background information, we saw a markedly reduced ipsilesional fixation bias in neglect patients, as compared to those scenes with many informative, widespread objects. The relation between the extent of ipsilesional fixation bias and the load of scene information (complexity) argues against a stable rightward deviation of egocentric space in neglect patients, as it is proclaimed by *transformation* theories (Ventre, Flandrin, & Jeannerod, 1984; Karnath, 1997). The dependency on the number and distribution of visual stimuli, that has also been found in studies with abstract visual stimuli (Sprenger, Kömpf, & Heide, 2002), is much better in line with an attentional model of neglect mechanisms (Kinsbourne, 1987). Accordingly, objects from both hemispaces compete for neglect patients' attention (Pouget & Driver, 2000) and contralesional items may succeed in the case of absence or reduced salience of ipsilesional items (Ishiai, 2006; Schnider, Blanche, & Ptak, 2011). The proposed neural basis are spatially selective neurons in the parietal lobes that integrate top-down and bottom-up inputs in an overall "attentional priority map" of items (Pouget & Driver, 2000; Itti & Koch, 2001; Fecteau & Munoz, 2006). Damage to the right hemisphere might lead to an underrepresentation of contralesional space in the attentional priority map, thereby causing left hemispatial neglect. Further support comes from a recent study using more abstract, static search arrays, where the pathological fixation bias in neglect patients has been counteracted by increasing the saliency of contralesional and decreasing the saliency of ipsilesional items (Bays, Singh-Curry, Gorgoraptis, Driver, & Husain, 2010).

4.2. Bottom-up influence of dynamic contrast and other physical scene properties

Following the theory of an imbalanced attentional priority map in the brain, we would expect neglect patients to fixate objects located further left in the naturalistic scene only if they are of higher saliency than objects on the right. In our naturalistic videos (as in the real world environment), the salience of objects as well as low-level scene features (brightness etc.) are changing constantly. In order to analyse local shifts of attention related to local scene properties, we used saliency maps that attributed the relative intensity of a specific feature (static contrast, dynamic contrast (motion), colour, brightness) to the part of a scene currently fixated (Itti & Koch, 2001; Böhme, Dorr, Krause, Martinetz, & Barth, 2006).

In healthy control subjects, our analysis confirmed that humans preferentially look at scene regions of either high static or dynamic contrast (Reinagel & Zador, 1999; Vig, Dorr, & Barth, 2009). Hence, in the free viewing condition, fixations of both healthy controls and RBDs landed on regions bearing higher values for static and dynamic saliency measures as compared to randomly sampled fixations.

In neglect patients, the intensity of static contrast at fixation was still higher across the whole visual field than expected by chance, but it was significantly lower than in controls. For the impact of dynamic contrast ("local motion"), there was a clear dissociation between ipsilesional and contralesional fixations: on the far right, patients' fixations landed on parts of the scene with significantly lower dynamic contrast than in controls. This may be explained by a pathological hyperattention for the ipsilesional hemifield (Kinsbourne, 1993) leading to a general rightward bias of fixations in neglect patients even when there is a lack of salient stimulus features. In contrast, the picture reversed for contralesional fixations landing on the left-hand side of neglect patients' peak of fixations. Here, the dynamic contrast at fixation was markedly increased, even above the absolute values of the control group. Thus, neglect patients' contralesional fixations seemed to be attracted by highly salient dynamic events, or in other words, patients' gaze may have shifted to the contralesional side only when there was intense local motion. However, these dynamic high-saliency features could still not overcome the strong ipsilesional fixation bias. According to the neglect model of an attentional gradient, this may be due to the widespread moving stimuli across the whole spatial reference frame, where ipsilesional stimuli of relatively low saliency are still powerful enough to draw patients' attention away from contralesional space.

4.3. Influence of top-down control during visual search in dynamic scenes

When a search task was introduced, controls could override bottom-up influences and their fixations in the periphery went to regions of lower saliency (static and dynamic contrast) than expected by chance. For example, controls were able to suppress fixating a moving car when they were searching for a stationary satellite dish. These results are consistent with previous findings on visual search in *static* images, where task-demands could overcome the attractiveness of salient objects (Einhäuser, Rutishauser, & Koch, 2008). Whereas control subjects used intact top-down control mechanisms during visual search and thereby overruled bottom-up influences, neglect patients failed to do so. Compared to healthy controls and the random fixation function in visual search trials, neglect patients fixated regions in the ipsilesional hemifield that contained higher static and dynamic contrast. This may indicate a lack of top-down control during visual search in the hyper-attended ipsilesional hemifield, where the influence of bottom-up features could not be suppressed.

In analogy, giving a task was not able to overcome the neglect patients' ipsilesional fixation bias in moving scenes. Previously, it had been shown for static visual search arrays, that the exploratory scanning behaviour of neglect patients could at least be altered by a specific task (Karnath & Niemeier, 2002; Baylis, Baylis, & Gore, 2004). However, we found that patients' global fixation distributions and saccade parameters in dynamic scenes did not differ between the free viewing and the visual search condition.

These findings of a profound lack of top-down influences on dynamic scene exploration are in line with previous studies that investigated the impact of top-down control on neglect behaviour. Although neglect patients have been shown to exhibit a different exploratory eye movement behaviour in the same visual stimulus array when the spatial reference frame (but not the stimulus itself) was changed by an external instruction, this was the case only for the absolute right hemispace (with reference to the body midsagittal plane) but not for the neglected left side (Karnath & Niemeier, 2002). In a different study, Sarri and colleagues reported that neglect behaviour was even exacerbated when a considerable amount of selective attention was required to select targets and filter-out non-targets in a search array, and that increasing task-demands on visual attention adversely affected spatial exploration (Sarri, Greenwood, Kalra, & Driver, 2009).

Our findings about neglect scanning behaviour in dynamic naturalistic scenes complement previous studies showing that bottom-up based stimulation techniques are superior to top-down approaches (e.g., external instructions or scanning training) in neglect rehabilitation (Kerkhoff, 2003; Parton et al., 2004; Chokron, Dupierrix, Tabert, & Bartolomeo, 2007; Kerkhoff & Schenk, 2012). In particular, those have shown positive and persistent effects on neglect behaviour which used optokinetic stimulation with abstract visual stimuli moving into the direction of the neglected hemifield (Kerkhoff, Keller, Ritter, & Marquardt, 2006; Schröder, Wist, & Homberg, 2008). In contrast to our study, however, the beneficial effect of oktokinetic stimulation appears more to be due to a direction-specific modulation of the egocentric midline than to the saliency of the moving stimulus. Based on the new insights of our study we propose that implementation of moving naturalistic stimuli in bottom-up stimulation schemes may be a promising candidate for improving neglect rehabilitation in the future.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.neuropsychologia.2012.06.012.

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