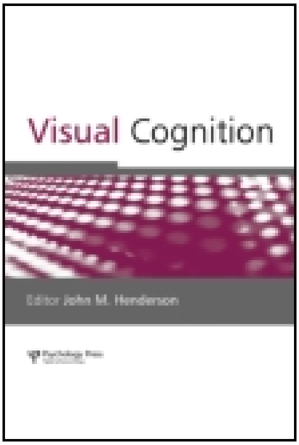

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Hide-and-seek around the centre of interest: The dead zone of attention revealed by change blindness

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Hide-and-seek around the centre of interest: The dead zone of attention revealed by change blindness

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Three experiments examined spatial allocation of attention during active search for visual changes. In all experiments, there were three conditions of change location related to a centre of interest: (1) Central (most attended location itself), (2) near, and (3) far marginal change. In Experiment 1, participants showed the slowest search and the largest number of undetected changes in near condition. Moreover, they misidentified near changes more frequently than central and far ones. In Experiment 2, participants had to search for marginal changes in the presence of a once noticed central change that summoned additional attention to a central location. It resulted in further search slowing for near changes. In Experiment 3, participants searched for one of two concurrent marginal changes in the presence of a central one. They detected far changes about 2.3 times more frequently than near ones. Taken together, these results support the notion of "dead zone of attention" surrounding attentional focus. Several speculations about the nature of dead zone are discussed.

Keywords: Change blindness; Dead zone of attention; Spatial attention.

Spatial distribution of attention is considered to be the one of significant determinants of visual perception and awareness. For instance, Treisman and

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Gelade (1980) stated that attention applied to a part of visual space provides accurate binding features in wholistic percept. In contrast, conjunctions of features may be incorrect in the absence of spatial attention (Treisman & Schmidt, 1982). According to Posner's framework, spatial distribution of attention is one of basic attentional functions termed as orienting (Posner, 1980; Posner & Fan, 2008). In numerous studies inspired by Posner (1980; Posner, Nissen, & Ogden, 1978) and Jonides (1981), it was revealed that spatial shifts of attention can accelerate responses to stimuli at locations previously cued by special signals (see Wright & Ward, 2008, for a comprehensive review).

However, amplification and enhancement of processing of target stimuli is not the only consequence of spatial attention. As was demonstrated in spatial cueing experiments, orienting of attention to a certain location has an inhibitory effect as well. This "dark side" of attentional processing was found in peripheral cue tasks. Posner and Cohen (1984) described a biphasic pattern of visual orienting to peripheral events. This pattern typically includes early facilitation and late inhibition of response to a cued target. The latter effect was termed *inhibition of return* (IOR). Posner and Cohen suggested that inhibition supports releasing of attention in favour of attending novel (uncued) locations. Klein (1988) came to a similar conclusion with visual search tasks. He found that observers detect probe stimuli more slowly if they occur at locations previously occupied by a distractor than at novel locations. Klein and MacInnes (1999) have also found that probe detection is also inhibited at recently foveated locations. As Danziger and Kingstone (1999) pointed out, IOR appears to occur immediately after the cue presentation but is masked by early short-term facilitation. The notion that spatial attention has both facilitative and inhibitory effects on performance is critical for other phenomena considered in this paper.

Another issue concerns allocation of attention around the attended location. Is there any inequality between near and far locations with respect to speed and accuracy of visual processing? If such inequality does occur, then which regions have a relative advantage in processing?

It appears that there is no unambiguous answer to these questions. Different patterns of results were obtained in different experiments. It is necessary to make a distinction between two classes of experimental situations studying spatial allocation of attention. The first class can be termed *fixation centred* allocation of attention. It includes experimental designs where destination of attention is manipulated in relation to a point of gaze fixation. Results are predominantly interpreted in terms of spatiotemporal resolution of retinal image. The second class of experimental procedures may be termed *attention centred*. Here, attention is summoned to a particular location or item by peripheral cues, central cues, or instructions. Distribution of efficiency is then analysed in relation to this attended location.

Fixation-centred experiments

Numerous fixation-centred experiments have been reported in the research literature, with tests of spatial distribution of attention over foveal, parafoveal, and peripheral regions of visual field. These will be considered only briefly here, as they have only an indirect relation to what will be tested in the present paper.

Many experiments with attentionally demanding tasks (such as visual search and change detection) have demonstrated that performance tends to decrease with eccentricity from fixation (Carrasco, Evert, Chang, & Katz, 1995; Tse, 2004; Wolfe, O'Neill, & Bennett, 1998). As Carrasco and colleagues have suggested, this eccentricity effect results from relatively low-level mechanisms such as spatial resolution of retinal image and corresponding neural pathways (Carrasco et al., 1995; Carrasco & Frieder, 1997). In contrast, Wolfe et al. (1998) proposed an alternative account of eccentricity effects, ascribing them to spatial distribution of attention around fixation rather than low-level visual mechanisms (see also LaBerge & Brown, 1986).

Another important finding about fixation-centred attention was made by Chen (2008) and termed *distractor eccentricity effect*. Her finding was that visual search is exposed to less interference from incompatible distractors at fixation, as compared to peripheral retinal locations. As Chen and Treisman (2008) suggested, this distractor eccentricity effect reflects gradient of attentional suppression that decreases with distance from fixation. At the same time, this suppression mechanism may also contribute to better attentional resolution at a fixation.

Attention-centred experiments

Experimental data obtained in several experiments carried out in order to extend the classical spotlight framework of attention (Posner, 1980) revealed a gradual decrement in speed and accuracy with distance from attentional focus (e.g., Castiello & Umiltà, 1990; Downing, 1988; Downing & Pinker, 1985; LaBerge, 1983). Observations made by Eriksen and colleagues (e.g., Eriksen & Eriksen, 1974; Eriksen & Hoffman, 1972; Eriksen & St. James, 1986) that flanker interference tends to reduce with distance were also adopted as evidence that spatial resolution of attention correlates positively with proximity to the centre. Results of several later experiments with inattentional blindness (Mack & Rock, 1998; Newby & Rock, 1998) and sustained inattentional blindness (Most, Scholl, Simons, & Chabris, 2000) supported this notion.

Nevertheless, another set of results obtained mainly over the past 10–15 years provide evidence against gradient model of attentional distribution and, as Cave and Bichot (1999) argued, against the spotlight framework as a whole. More precisely, these results limit the extent to which allocation of attention may be explained by the spotlight model alone. Thus, several experimental studies have documented inhibitory surrounds near the focus of attention in various tasks such as visual search, probe detection or identification, inattentional blindness paradigm, etc. (e.g., Bahcall & Kowler, 1999; Caputo & Guerra, 1998; Cave & Zimmerman, 1997; Cutzu & Tsotsos, 2003; Mounts, 2000a, b; Müller, Mollenhauer, Rösler, & Kleinschmidt, 2005; Thakral & Slotnick, 2010). Several neurophysiological studies have also supported the notion of inhibitory surrounds near attentional focus (Boehler, Tsotsos, Schoenfeld, Heinze, & Hopf, 2009; Hopf et al., 2006; Müller & Kleinschmidt, 2004; Slotnick, Hopfinger, Klein, & Sutter, 2002). Also of note, similar inhibitory surround patterns were earlier documented for temporal distribution of attention; thus, attentional blink effect is a failure to detect a probe item within 300–400 ms of target presentation (Raymond, Shapiro, & Arnell, 1992).

Therefore, two distinct patterns of centre-surrounding spatial attention were observed in experimental studies. How can theory incorporate both patterns while avoiding contradiction? Probably, the solution lies in the limitation of generalization by some specific conditions. Task load on central attention may be considered as one such condition. It appears that task demands elicited by the processing of a centrally attended location mediate allocation of attention around the centre. For example, in experiments by Cave and Zimmerman (1997) and Mounts (2000b, 2005) it was found that inhibitory surrounds arise when attentional salience is large enough at a centrally attended location. On the other hand, task difficulty may also affect inhibitory surrounds through central attention demands. For instance, Müller et al. (2005) found that the amount of flanker interference from proximal distractors tends to increase with task difficulty. Thakral and Slotnick (2010) found two opposite spatial distributions of inattentional blindness to a probe stimulus depending on primary task accuracy (which indirectly reflects subjective task difficulty). They reported that their participants with good primary task performance noticed proximal unexpected probes more frequently than distant ones. In contrast, participants with intermediate levels of primary task accuracy demonstrated a poorer detection rate at proximal locations than at distant ones.

Another probable explanation for the two contradictory spatial patterns is considered by Müller et al. (2005). They suggested that this may be due to different attentional sets towards stimuli. Gradient of attentional distribution is typically observed when only one stimulus is attended while others are ignored. For example, an Eriksen-type task implies such a set with one attended letter and equally salient flankers. In contrast, inhibitory surrounds are more typical for tasks where the two locations are attended due to dual task instructions (e.g., Bahcall & Kowler, 1999; Cave & Zimmerman, 1997) or involuntary attentional capture by salient distractor (e.g. Mounts, 2000a, b). One explanation is that two separate items are competing for prior processing within an attentional field. It is likely that an attentionally salient or predictive item wins the competition and suppresses its neighbour (Desimone & Duncan, 1995; Mounts, 2005). This competition is more dramatic between proximal objects than between distant objects since it is more likely that proximal representations take place within common receptive fields sharing neural resources (Desimone & Duncan, 1995). Alternatively, inhibitory surrounds reflect a selective tuning mechanism, that is, active suppression of a task-irrelevant distractor (Cutzu & Tsotsos, 2003).

THE PRESENT EXPERIMENTS

All the papers cited earlier were concerned mainly with tasks in which allocation of attention is limited by specific viewing conditions. First, participants have to maintain fixation at a central point while allocating attention covertly (both in fixation-centred and attention-centred paradigms). Second, experimental displays typically include relatively simple sets of discrete objects on homogenous background.

Manipulations with fixation and artificial displays are widely recognized as effective tools to provide psychophysical control of artefacts in attentional experiments. However, they provide insufficient information on how attention operates in more naturalistic perceptual conditions. In such conditions, observers are typically able to move their eyes freely. Besides, natural scenes include more complex object layouts than artificial arrays typically provide. For example, as was pointed out by Wolfe (1994), continuity of objects in naturalistic scenes (as opposed to their discrete presentation in arrays) may be considered as a significant factor complicating visual search. Moreover, in natural scenes objects usually vary in the degree to which they are critical for sense extraction and wholistic scene perception. Thus, attention may be manipulated via internal interest factors along with externally controlled cues, abrupt onsets, singletons, instructions, etc.

The one effective tool to study spatial distribution of attention over natural scenes perception is the change blindness paradigm. Its efficiency is provided by two features of the paradigm. On the one hand, change blindness is suitable for studying some spatial properties of attention (e.g., Tse, 2004). This suitability is based on the notion that focusing of attention on a certain location is necessary to produce a coherent representation of an object. Coherent representation, in turn, permits to track an attended object in order to see any perceptual events happening to it (Kahneman, Treisman, & Gibbs, 1992; Rensink, 2000). Consequently, focused attention appears to be the critical condition for perceiving visual changes to objects (Rensink, 2000; Rensink, O'Regan, & Clark, 1997; Scholl, 2000). On the other hand, the change blindness paradigm is also an effective tool for studying how attention operates in naturalistic scenes with free eye movements. Manipulations with factors of interest are also available in this paradigm. The critical result obtained by Rensink et al. (1997) was that observers tend to detect changes in interesting (central) objects better than in uninteresting (marginal) objects. A similar result was found by Turatto and Bridgeman (2005) for change identification.

Three change blindness experiments were conducted to examine spatial allocation of attention around a centre of interest in visual scenes. Factors of interest and spatial distribution of changes were manipulated during these experiments.

Several presumptions may be stated with respect to expected results. First, it is almost certain that change detection performance at any marginal location should be poorer than at a centre of interest (Rensink et al., 1997). Second, it is expected (on the grounds of the earlier literature review) that attention would allocate in an uneven fashion between marginal items at different eccentricities. Nevertheless, previous experimental data assume two alternative ways of attentional allocation: Gradient mode or inhibitory-surrounding mode. If the gradient mode of allocation takes place, then change detection performance should decrease with distance from a centre of interest. In contrast, if the inhibitory-surrounding mode is the case, then change detection performance at near locations should be poorer than at further locations.

EXPERIMENT 1

Methods

Participants. In total, 55 management students of the Higher School of Economics (mean age 18 years, 18 males) participated in the experiment for extra credits in a psychology course. They reported having normal or corrected to normal vision.

Apparatus and stimuli. Stimulation was developed and presented through StimMake software (authors A. N. Gusev & A. E. Kremlev). Stimuli were presented on a standard VGA monitor with a refresh frequency of 85 Hz and a spatial resolution of 800 × 600 pixels.

Fifteen pictures of natural landscapes, buildings, and animals were used in the experiment. Twelve pictures were used in the main block of trials and three other pictures were used only for training purposes.

Pictures used in the main experimental block were specially selected in the course of a two-stage procedure aimed to provide stimuli with only one attractive (central) object or part of an object surrounded by numerous marginal details. The first stage included a modified procedure by Rensink et al. (1997) to reveal central and marginal interests. Seventeen naïve observers were exposed to 16 pictures and asked to make a brief description of each picture emphasizing the main detail. The criterion of selection was at least 75% observers reporting the same main detail. According to that criterion, 14 out of 16 pictures passed through the first stage of selection. In the second stage, nine naïve observers who hadn't taken part in the first stage looked at the same 16 pictures. Their eye movements were registered with an SMI RED III eyetracker with a refresh frequency of 50 Hz. In order to analyse the distribution of gaze fixations, the pictures were divided into segments containing the main object and few other objects frequently reported by observers in the first stage. If the main object was large (more than 4° of visual angle), it was subdivided into several smaller segments. The measure of visual interest to a segment was total fixation time of that segment during the whole observation period. A picture was made available for further experiments if the segment of maximum visual interest coincided with the reported main object, and its fixation time was at least three times longer than that for other segments. This process resulted in 12 pictures satisfying the criteria. Segments of maximum fixation, in turn, were considered as *centres of interest*.

Three pictures for the training block were chosen from stimuli previously used in change blindness experiments in our laboratory. These pictures didn't go through any special selection procedure and were used only to make the change detection task familiar to observers. Each of these three training pictures had one modification.

Each of 12 main block pictures had three modifications depending on the change location. The first modification included a change in a central object or in a centrally attended area of a large object. The second modification included a change in a marginal object near a central one (~5° in average from the conditioned centre of an interesting area, ranging from ~2° to ~8°), and the third modification contained change in similar marginal object far from the centre of interest (~19° in average from the conditioned centre, ranging from ~13° to ~25°). Thus, the maximum distance of near changes never overlapped with the minimum distance of far changes. Three change instances for each picture have been labelled as (1) central, (2) near, and (3) far, respectively. All near and far changes were proximately equated with respect to their visual sizes (~2 sq. degrees on average for both types, ranging from ~.6 to ~6 sq. degrees), colour, and contrast. Moreover, marginal changes were made to the objects of the same type within each picture (e.g., both trees, both rocks, both shadows, etc.). Therefore, proximity to the centre of interest was the only parameter manipulated with respect to objects of marginal interest. Moreover, marginal changes were placed in different directions from the centre across the pictures to achieve approximately uniform spatial distribution of targets over the screen. Figure 1 shows an example of original and modified pictures for the three conditions of change location.

An additional test was conducted to show that (1) changing objects are perceived unambiguously (absolute identity) and (2) near and far marginal objects are perceived as identical within each picture (relative identity). This allowed the control of semantic factors affecting the degree of interest for particular marginal objects. Eleven naïve observers were serially exposed to all 36 possible changes (12 pictures $\times$ 3 instances of changing details) under an unmasked condition, that is, they saw visual alternations without interruptions by the blank screen. This allowed full attention to change locations. Observers were asked to verbally describe changing details. There were 1.2% discordant responses between observers in identifying every single object and 3.2% discordant responses in identifying near and far changing details as the same objects within each picture. Both values were below standard statistical error (.05) and, thus, both absolute and relative identities were considered to be achieved.

Procedure. Participants were seated about 50 cm from the monitor. They were instructed to search for a changing detail in two alternating pictures. As soon as participants noticed a changing detail they had to press the Y button on the keyboard and say what has changed. They were also allowed to miss responses if they failed to see any change over a long period of time; for this, participants had to press the Y button and say that they were unable to find anything. The time limit of search for one change was 5 minutes.

The flicker paradigm was used for stimuli presentation. Thus, original (A) and modified (A′) pictures alternated repeatedly on the screen. A blank grey field was inserted between every change of the pictures. The duration of a picture presentation was 400 ms and the blank field duration was 200 ms. The full alternation comprised the sequence "A–blank–A′–blank". Hence, one full alternation cycle lasted 1.2 s. The flicker stopped as soon as participant pressed the Y button. The original version of Picture A stayed on the screen while participants were reporting what had changed. Pressing the Y button again caused the next trial to begin.

At the beginning of the experiment participants received three practice trials followed by 12 experimental trials. The 12 experimental trials included four trials with central change, four trials with near change, and four trials with far change. Trials of all types were intermixed in quasirandom order excluding two trials of the same type at adjacent serial positions. Each picture presented only once per participant with only one of three possible changes. Change

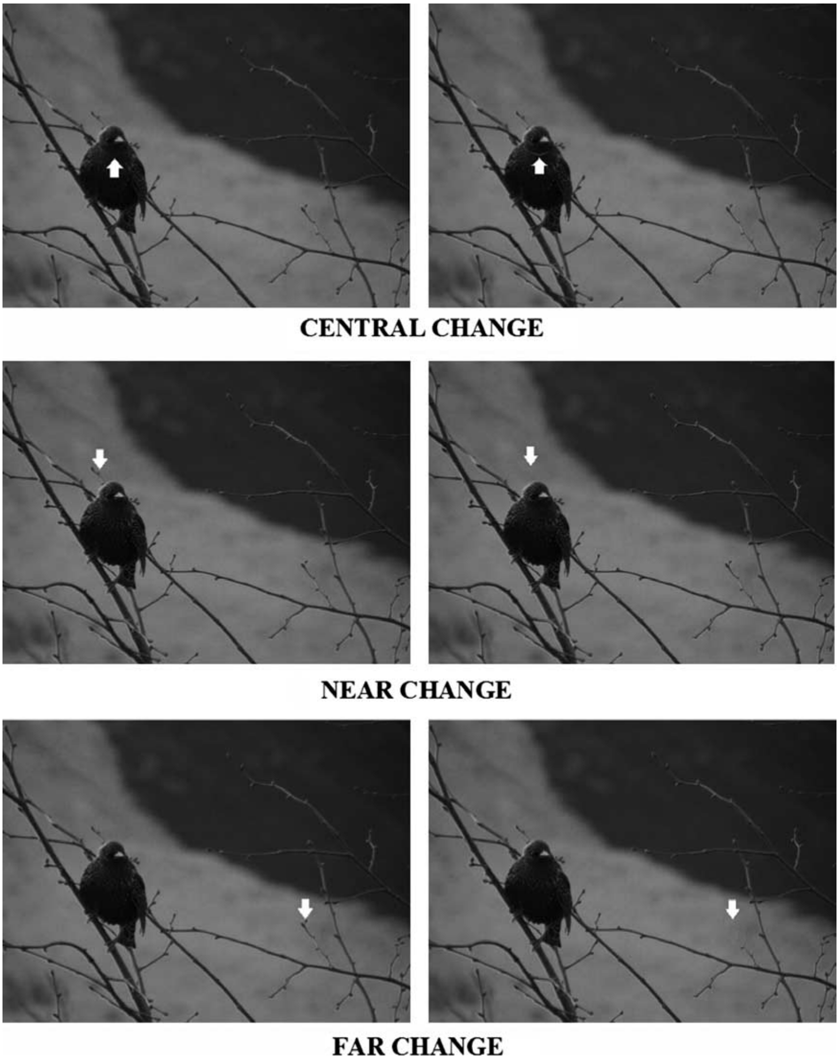

Figure 1. Example of a picture with three modifications showing the three instances of change location used in the experiments. Modified details are indicated by the white arrows.

locations for each picture varied across participants. Hence, one-third of participants received a "central" instance of a given picture, one third received a "near" instance, and one third received a "far" instance.

Design. There was only one within-subject independent variable in the experiment. This was *change location*, which included three conditions: Central, near, and far.

Dependent variables were as follows: (1) Median search time (only for trials with successfully detected changes, without miss responses), (2) missed changes (participants pressed the key and reported that they failed to see any change), and (3) misidentifications. Search was considered successful if a participant eventually noticed a change at a correct location (independently of success in change identification). Misidentification errors included all cases when a participant succeeded in change detection of an object that had actually changed but failed to recognize the object itself or its change correctly. For example, a participant reported seeing the shadow cast by a flying aeroplane on the earth, where in fact green bushes appear.

Results

Of the experimental trials, 3.5% were admitted invalid and excluded from data analysis. These were due to computer program errors, accidental key pressings, or false detections (participants pressed the key and reported seeing a change to an object that was in fact unchanged).

Table 1 summarizes experimental results under the three conditions of change location.

Series of nonparametric Mann-Whitney tests of search time revealed that there were significant differences between central and near conditions, $U = 5077$, $p < .001$, central and far conditions, $U = 8567.5$, $p < .001$, and near and far conditions, $U = 8763.5$, $p < .001$.

A chi-square test was applied to the analysis of error rates. It revealed significant differences between distributions of missed changes, $\chi^2(2) = 53.82$, $p < .001$, and misidentifications, $\chi^2(2) = 35.67$, $p < .001$, in all three experimental conditions. All paired differences were also significant. In both cases, minimum error rates were achieved in the central condition and maximum error rates were achieved in the near condition.

TABLE 1
Median search times and error percentages in three experimental conditions of Experiment 1; successful search trials exclude missed changes and invalid trials

		Change location		
		Centre	*Near*	*Far*
Time of successful search (s)	*N*	207	142	170
	Median	4.93	39.96	20.95
Missed changes	*N*	11	70	47
	% valid trials	5.0	33.0	21.7
Misidentifications	*N*	5	37	12
	% valid trials	2.3	17.5	5.5

Discussion

According to experimental results, participants showed significant change blindness. However, the magnitude of that blindness depends on change location. Thus, changes in centres of interest (central changes) are detected more rapidly and more accurately than other details (objects of marginal interest). Both detection (Rensink et al., 1997) and identification (Turatto & Bridgeman, 2005) patterns indicate the lack of attention to marginal changes.

As for marginal changes, it was revealed that their location may actually affect a person's ability to detect and identify them. As seen in Table 1, change detection performance was significantly poorer under the near condition than under the far condition. Participants spent more time finding a change near a centre of interest. Near changes remained unnoticed (missed) more frequently than far ones. Finally, participants tend to make more identification errors in the near condition. All the results of Experiment 1 indicate, therefore, the same phenomenon of exaggerated change blindness to objects near a centre of interest.

Results of the present experiment provided preliminary evidence that a phenomenon akin to inhibitory surround (see previously for review) does take place near centres of interest in visual scenes.

Nevertheless, the present experiment does not allow unambiguous identifying observed phenomenon as inhibitory attentional surrounds. First, there is insufficient evidence that it is due to attention. Second, several interpretations other than inhibition are possible. For example, strategy of search may affect change detection performance as well. For these reasons, I prefer to use wider term "dead zone" for the obtained pattern. In my opinion, it is well suited for both inhibitory and noninhibitory accounts of observed effects.

The next step of the present study was aimed to approve that the "dead zone" arises from allocation of attention to a centre of interest.

EXPERIMENT 2

Experiment 1 provided primary observation that marginal objects near a centre of interest are processed more poorly than those far from that centre. Nevertheless, there are still some restrictions concerning experimental design. These restrictions may affect the interpretation of this primary pattern in terms of spatial allocation of attention. As soon as pictures of natural scenes were used, complete counterbalancing of all parameters became problematic. Although sensory and semantic characteristics of both near and far changes were made approximately equal, they still remained naturally variable. Some of their variations reserve the likelihood of uncontrolled effects other than those of the focus-related spatial position.

For instance, as soon as centrally attended objects tend to be placed around the screen centre, it becomes likely that the primary spatial pattern is associated with the centre of the search space rather than the interest itself. The similar "centration effect" has been described in other earlier change blindness research (Galpin, Underwood, & Crundall, 2009).

Experiment 2 was conducted to assert that the primary spatial pattern is in fact associated with attention towards a centre of interest. If this is the case, then additional attention drawn to that centre should impair detection of changes to marginal details. If the attention-centred "dead zone" hypothesis is true, then the most dramatic impairment is expected at near locations. That is, exaggerated change blindness is expected for near objects, as compared to Experiment 1.

The important methodological issue concerns manipulations by which attention could be additionally attracted to a centre of interest. One way is exogenous control of involuntary attention by irrelevant external events such as abrupt onsets (Yantis & Jonides, 1984). Such abrupt onset cues were successfully used in other change blindness experiments (Rensink et al., 1997; Scholl, 2000). Unfortunately, it is difficult to maintain involuntary attention during a prolonged period of search by a single abrupt onset. On the other hand, serial abrupt onsets can produce undesirable confounds (for example, systematic masking effects, that are especially critical for adjacent spatial positions). The other way to attract additional attention to a central object or its most interesting part is a special task concerning it. For example, participants may be instructed to remember a central object in detail and report this after experiment. This manipulation encourages central attention to be maintained for quite a long period of time. However, it is also problematic. First, it precludes participants from free scanning of a picture. Second, such an additional task could produce an extra load on attention and visual working memory that may affect spatial allocation of attention in an unpredictable way.

Quite a suitable solution lies in the change blindness paradigm itself. It arises from the fact that a once noticed change becomes so salient that it can hardly be ignored during further observation. Attraction of attention to a once noticed change does not imply any additional external events beyond the standard flicker paradigm or any extra load by a secondary task. In Experiment 2, participants had to search for marginal changes (near or far) in the presence of a once noticed central change.

Methods

Participants. In total, 26 psychology students of the Higher School of Economics (mean age 19 years, nine males) participated in the experiment

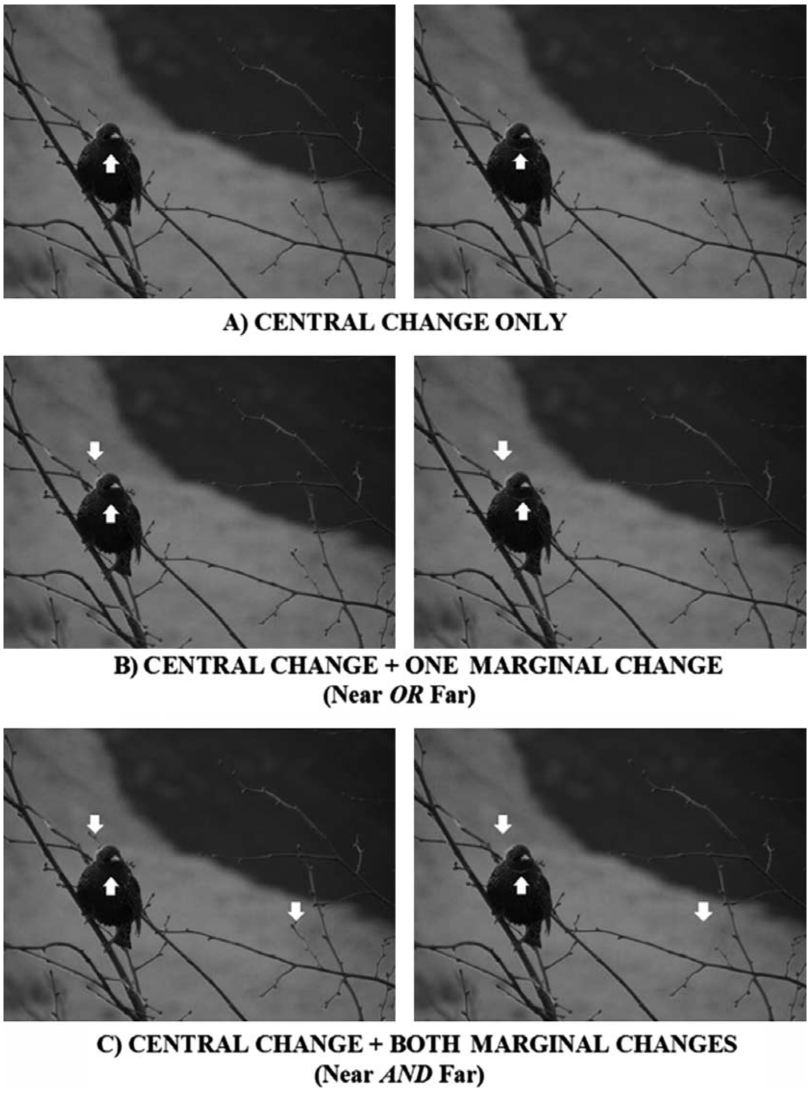

Figure 2. Picture modifications used in Experiments 2 and 3. (A) Central change used only in set stage of both experiments. (B) Central change and one marginal change used in probe stage of Experiment 2. (C) Central change and both marginal changes used in probe stage of Experiment 3.

for extra credits in their course of experimental psychology. They reported having normal or corrected to normal vision. None of them had taken part in Experiment 1.

Apparatus and stimuli. The apparatus was mainly identical to that in Experiment 1. The only addition was the special device for response registration used instead of a standard computer keyboard. It was the parallel port-compatible control panel designed for reaction time experiments. The construction of the control panel provided a short distance between the top (unpressed) and bottom (pressed) positions of its keys. This provided precise measurement of reaction times that was better than that of any key of a standard computer keyboard.

The pictures used in the Experiment 2 were the same as in Experiment 1. Changes made to objects were identical to those in Experiment 1.

Another modification brought by Experiment 2 was in the report procedure. Participants had to make a written report about changes they noticed, instead of an oral report registered by the experimenter. A specially designed brochure was used for the written report. This made for better control of the Pygmalion effect (Rosenthal, 1976; Rosenthal & Jacobson, 1968).

Procedure. Participants were seated about 50 cm from the monitor. They had to perform change detection under flicker conditions.

After two practice trials, participants had to pass through the main block of trials that consisted of two serial stages. In the first *setting* stage, they had to detect and describe a single change in each of 12 pictures. All the changes were in the centre of interest (Figure 2A). At the end of this stage, the experimenter checked the responses made by participants. If a participant made any mistakes in change detection or recognition, the experimenter indicated correct changes in the corresponding pictures.

In the second *probe* stage, participants were instructed to search for other changes in the same set of pictures in the presence of the central changes noticed earlier or indicated by the experimenter (Figure 2B). All the second changes were marginal in this stage of experiment. Half of these changes were

TABLE 2
Median search times and error percentages in three experimental conditions of Experiment 2; successful search trials exclude missed changes and invalid trials

		Change location		
		Centre	*Near*	*Far*
Time of successful search (s)	*N*	319	86	123
	Median	4.17	52.72	25.61
Missed changes	*N*	1	53	30
	% valid trials	0.3	38.1	19.6
Misidentifications	*N*	7	17	3
	% valid trials	2.9	12.2	5.5

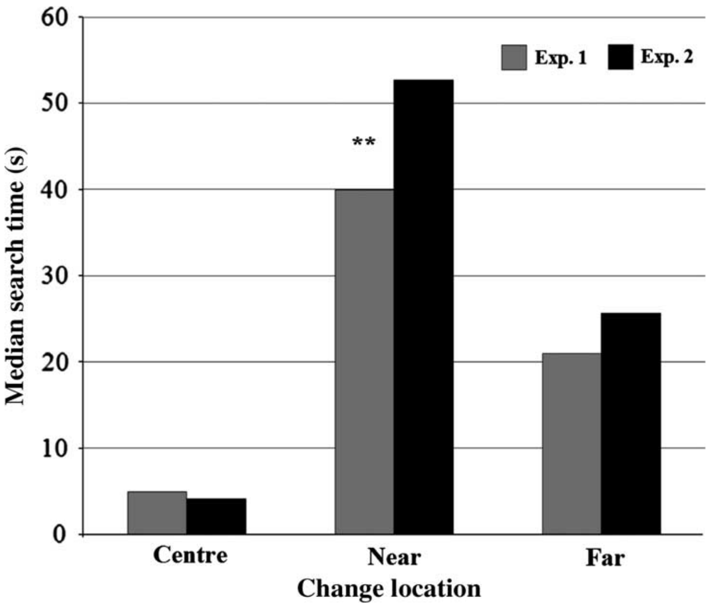

Figure 3. Effects of change location on search time in Experiments 1 and 2. $^{**}p < .01$

near a centre of interest and the other half were far from that centre. Marginal change locations for each picture varied across participants. Therefore, in the second stage of the experiment, half of the participants received a "near" instance of a given picture, and the other half received a "far" instance.

Design. Change location was the only within-subject independent variable. Dependent variables were the same as in Experiment 1.

Results

A total of 4.8% experimental trials were admitted invalid and excluded from data analysis for the same criteria as in Experiment 1.

Table 2 summarizes experimental results under three conditions of change location.

Series of nonparametric Mann–Whitney tests of search time revealed significant differences between central and near conditions, $U = 1803$, $p < .001$, central and far conditions, $U = 5221.5$, $p < .001$, and near and far conditions, $U = 3319.0$, $p < .001$.

The chi-square test was applied to the analysis of error rates. It revealed significant differences between distributions of missed changes, $\chi^2(2) = 108.49$,

$p < .001$, and misidentifications, $\chi^2(2) = 22.58$, $p < .001$, in three experimental conditions. All paired differences were also significant. In both cases minimum error rates were achieved in central condition and maximum error rates were achieved in near condition.

Series of statistical tests were made to compare differences between results of Experiments 1 and 2. Independent-sample Mann-Whitney tests revealed significant difference between search times in the near condition, $U = 4857.0$, $p < .01$. Paired chi-square tests revealed significant difference between miss rates in central conditions of two experiments, $\chi^2(1) = 13.37$, $p < .001$. No other differences were significant.

Figure 3 illustrates the search time results of Experiment 2 as compared to those of Experiment 1.

Discussion

The results of the present experiment replicated the main observation from Experiment 1 that centrally attended regions appear to be surrounded by a dead zone. Change detection performance was poorer inside this dead zone than in the far periphery of the visual scene. This is seen from the temporal characteristic of both search and error rates.

In contrast with Experiment 1, additional attention was attracted to the centres of interests by persisting changes inside these centres once they were noticed by participants. On the one hand, this manipulation had no effect on error rates, as compared to the Experiment 1; on the other hand, it had a relative effect on search time.

The most important outcome of manipulation with central changes was the relative prolongation of visual search for a change at near locations as compared to Experiment 1. It is notable that change detection remained unimpaired at far locations. This indicates that amplification of change blindness to marginal changes by central changes is mediated by change location.

As soon as change detection is supposed to be near impossible without attention under flicker conditions (Rensink, 2000; Rensink et al., 1997), then it is likely that search prolongation at near locations should be due to irresistible allocation of attention towards a central change. It is hardly possible that such an impairment of change detection at near locations is elicited by lower level sensory mechanisms affecting spatiotemporal resolution of vision. In other words, results of the present experiment provide evidence that exaggerated change blindness at locations near the centre of interest reflects dead zone of attention.

Converging evidence that this dead zone pattern is associated with attention comes from earlier attention-centred experiments. It is based on the finding that manipulation with attentional salience of centrally attended locations in Experiment 2 produced essentially the same effect. For instance, Mounts (2005) found that visual search for a singleton-adjacent target tends to slow down with singleton salience. A similar prediction was considered by Müller et al. (2005) with respect to amplification of inhibitory surround with growth in central attention demands.

EXPERIMENT 3

Experiment 3 provides an alternative way to measure what was investigated in Experiment 2. As in Experiment 2, once noticed central changes were introduced to summon and maintain attention at a central location. The principal feature of this experiment was that both near and far changes were presented concurrently to compete for prior detection. According to the "dead zone" hypothesis, far changes should win the competition for detection more frequently than near changes do. The results of Experiments 1 and 2 provide estimations of mainly temporal characteristics of attentional allocation during search for marginal changes. The results of the present experiment, in contrast, should provide a probabilistic measure of attentional allocation. It will indicate how frequently far and near locations are attended to create a coherent representation that will suffice for conscious perception of a change.

Methods

Participants. In total, 25 psychology students of Higher School of Economics (mean age 19 years, four males) participated in the experiment for extra credits in their course of experimental psychology. They reported having normal or corrected to normal vision. None of them had taken part in Experiments 1 or 2.

Apparatus and stimuli. The apparatus and stimuli were mainly identical to those in Experiment 2. The only exclusion was that picture modifications used in the probe stage included all three possible changes at once (Figure 2C).

Pictures used in the Experiment 3 were the same as in Experiments 1 and 2. Changes made to objects were identical to those in Experiment 1.

Procedure. The experimental procedure was analogous to that used in Experiment 2. The only modification was that both near and far changes were presented concurrently during the probe stage of the experiment. Nevertheless, participants were instructed to look for only one marginal change in the probe stage. They remained ignorant about another marginal change until the end of the experiment.

Design. The independent variable was the same as in Experiments 1 and 2. The principal dependent variable was change detection probability in either near or far marginal detail. Search times for near and far detected changes were also measured. It was necessary to control whether probability measures obtained for each response represent identical temporal cuts of change detection. Identity of temporal cuts should warrant that probabilistic measures are obtained at essentially the same moments of viewing.

Results

In this experiment, missed changes were discarded as invalid trials along with false detections and accidental key pressing. This was done because missed changes are uninformative about change location in competition conditions. The total number of invalid trials was equal to 21.7%.

The average probability of change detection at near locations was equal to .30 ($SD = 0.17$). Average probability of change detection at far locations was equal to .70 ($SD = 0.17$).

Paired-samples t-test revealed a highly significant effect of marginal change location on change detection probability. $t(24) = -6.04$, $p < .001$.

Median search time was 21.8 s for near response trials and 16.6 s for far response trials. Mann-Whitney test failed to show significant difference between them.

Discussion

As can be seen from the results, far changes tended to win the competition for prior detection about 2.3 times more frequently than near changes do. This finding provides converging evidence for the dead zone of attention under change blindness conditions.

As can be inferred from search time analysis, probability measures obtained for near and far responses do actually represent the same temporal cut of change detection.

GENERAL DISCUSSION

In the series of three experiments it was found that attention is allocated in an uneven fashion around the centrally attended region. It appears that this allocation is carried out in an inhibitory-surround rather than a gradient fashion. That is, change detection and identification were found to be poorer for marginal details near the attentional focus driven by interest (Experiment 1) and/or capture of awareness (Experiments 2 and 3). It appears that this inhibitory-surrounding mode of allocation is consistent with suggestions made by Müller et al. (2005) and Thakral and Slotnick (2010) about factors mediating allocation patterns, such as task load on central attention and attentional set towards selected stimuli. In the present case, both factors are related to the attentional salience of centrally attended locations. First, high attentional salience of centres of interest implied rather large attentional load on these regions along with cost in disengagement (cf. Cave & Zimmerman, 1997; Mounts, 2000a, 2000b), especially in Experiments 2 and 3. Second, the cost of disengagement from a centre of interest implies that attention has to deal with two targets at once rather than a single target. That is, the salient centre of interest captures attention involuntarily, while the search for another marginal change is being carried out. According to Müller et al., these two features should define inhibitory-surrounding rather than gradient allocation of attention around the centrally attended region.

However, it is not necessarily the case that exaggerated change blindness at near locations is due to spatial inhibition alone, at least as it is understood by other authors. Both gradients and inhibitory surrounds were observed in rather specific experimental conditions. Brief trials with simplistic arrays typically imply a single spatial focus of attention (or at least a single predominant focus) with spreading patterns of activation and inhibition. In these terms, activation and suppression are considered as rather static formations. Both gradient and inhibitory-surround accounts reflect a predominantly static aspect of attentional allocation.

It is obvious that this static view of attention is insufficient to understand the processes of active search for changes used in the present experiments. Scrutinized search during dozens of seconds in naturalistic scenes rich with details can hardly be based on a single focus of attention (especially when eye gaze is not strictly fixated on one point). It is more likely that a series of attentional shifts are carried out during such a search. Hence, comprehensive explanation of obtained spatial pattern should incorporate both static and dynamic aspects of attentional allocation. From this viewpoint, terms used elsewhere in cited papers to describe predominantly static inhibitory patterns (e.g., Caputo & Guerra, 1998; Cutzu & Tsotsos, 2003; Mounts, 2000a, 2000b, 2005; Müller & Kleinschmidt, 2004, Müller et al., 2005; Thakral & Slotnick, 2010, etc.) seem to be inappropriate in the present context. For this reason, I prefer to use more general term "dead zone of attention" here. Dead zone is a metaphor that originates from car-driving terminology where it is used as a label for the left and right spatial regions around a driver falling out of direct gaze and the zone observed through the rear-view mirrors. Here, the view in front of a driver may be considered as the most attended direction, similar to a centre of interest. The rear view is typically attended to from time to time and is akin to marginal interests in the change blindness paradigm. Finally, the dead zone is the less visible region between the two directions that demands special activity in order to be in sight; this activity will certainly require some degree of disengagement from looking forwards. Similarly, the dead zone of attention lies between the central and the far marginal locations and requires disengagement from the centre to be seen. The latter conclusion follows from the finding that change blindness to near locations persisted for a longer time with externally capturing central events (Experiment 2) than with just interesting central objects (Experiment 1) which are probably easier to ignore. The concept of dead zone of attention is more suitable to catch a dynamic aspect of attentional allocation.

There may be at least four speculations about the possible explanation of a dead zone pattern obtained in a change blindness task like the one used in the present study.

1. Suppression hypothesis. This hypothesis presumes a relatively low-level explanation of the dead zone pattern. The explanation is based on reflexive sensory mechanisms controlling spatial activation and inhibition. It may be subdivided into the two versions.

1a. Inhibitory surrounds. According to this hypothesis, the mechanism underlying the dead zone of attention is quite similar to the one underlying

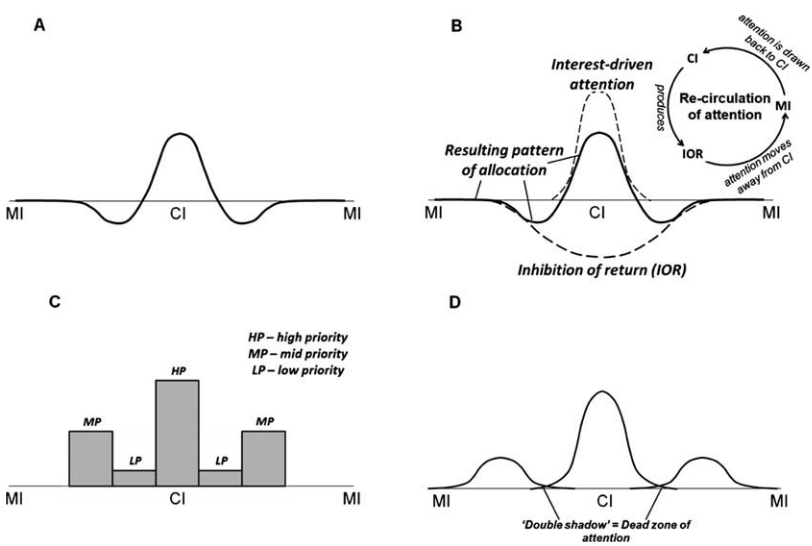

Figure 4. Possible hypotheses explaining dead zone of attention. CI = centre of interest; MI = marginal interests. (A) Inhibitory-surround explanation. (B) Explanation based on inhibition of return (with recirculation of attention scheme). (C) Waiting list metaphor (with spatial distribution of priorities in attending). (D) "Double shadow" explanation.

inhibitory surrounds in previously described studies (Caputo & Guerra, 1998; Cutzu & Tsotsos, 2003; Hopf et al., 2006; Mounts, 2000a, b, 2005; Müller & Kleinschmidt, 2004; Slotnick et al., 2002; Thakral & Slotnick, 2010). That is, attentionally salient (central) objects tend to draw and maintain focal attention that is then surrounded by an inhibitory window. This inhibitory window may arise due to biased competition for neural resources when a attentionally salient item suppresses its neighbours (Duncan & Desimone, 1995; Mounts, 2005). Alternatively, suppression may reflect an efficient mechanism of inhibition towards irrelevant distractors that preserves centrally attended representation from interference (Cutzu & Tsotsos, 2003). A similar distractor suppression mechanism was found in fixation-centred tasks (Chen, 2008; Chen & Treisman, 2008). The fact that the misidentification rate is rather high in the dead zone is consistent with the inhibitory surround framework (cf. Mounts, 2000a). The inhibitory surround explanation is schematically shown in Figure 4A.

1b. Inhibition of return (IOR). This is the more dynamic version of suppression explanation. It presumes that several serially repeated processes define distribution of attention in dead zone fashion. Here, central attention and IOR appear to be separate processes, as was suggested by Danziger and Kingstone (1999). At the beginning, allocation of attention to a centre of interest *causes* subsequent inhibition of attended location in favour of novel locations (Klein, 1988; Posner & Cohen, 1984). This IOR process, in turn, makes attention *move away* from attended location. It appears that IOR tends to spread beyond the originally attended location; however, its magnitude tends to decay with distance (Bennett & Pratt, 2001; Samuel & Kat, 2003). Therefore, IOR should possess both centrally attended and proximal locations. Meanwhile, internal interests or external events (such as once noticed changes from Experiments 2 and 3) make attention *move back* to a centrally attended location. If factors drawing attention back are enduring enough, then their facilitative effect is able to overcome IOR at an attended location. If this facilitative window is narrower than the inhibitory window, then Mexican-hat distribution of performance takes place (Figure 4B). But once attention is back to a previously attended location it releases more IOR. Therefore, a series of operations moving attention away and back should repeat. This is what may be termed as *recirculation of attention* (Figure 4B). Recirculation of attention appears to be a good explanation of long-lasting change blindness in the dead zone observed in my experiments. However, the whole IOR-based explanation appears unlikely for the present experiments because of scene interruptions used in change blindness paradigm. Several other researchers have replicated the finding that IOR is removed when the initial visual scene is interrupted (Klein & MacInnes, 1999; Müller & von Mühlenen, 2000; Takeda & Yagi, 2000).

2. Figure–ground hypothesis. This hypothesis is based on the link between attentional salience and figural emphasis (Kahneman, 1973). It is most likely that centrally attended objects are treated as figures while their surrounds are treated as background and, thus, are ignored. It is a very effortful task to revert figure–background relations when the salient object is presented in close proximity to the changing marginal target. It is probably much easier to treat a marginal detail as a figure when the salient region is placed far away from the current focus of attention. Consequently, marginal changes at the far periphery are better emphasized as figures than marginal changes at the proximal periphery.

3. Waiting list hypothesis. According to this hypothesis, the dead zone of attention reflects spontaneous strategy of search for a change rather than centre–surround inhibition. Given that this search takes time and requires multiple shifts of attention over the scene, it is possible that the cognitive system controls this process by some general plan. Certainly, this plan may be modified many times during the searching process, depending on particular objects, their layout, previous search results, etc. Nevertheless, a rough spatial sketch of this plan (or scheme) may stay relatively stable and precede accumulation of information about objects and their changes (Neisser, 1976). This spatial sketch probably includes order of scene exploring. This is well described by the *waiting list* metaphor, which defines priorities given to certain locations. Priorities in the waiting list involve order and frequency of attendance as well as time spent at these locations. Taken together, order, frequency, and time cause more or less successful change detection and identification. High priority in the waiting list is probably the simplest explanation of good detection and identification of attentionally cued (Scholl, 2000), interesting (Rensink et al., 1997), or highly probable (Turatto & Bridgeman, 2005) changes. Middle priorities are given to locations where marginal objects are placed. Finally, the lowest priorities are given to locations near a centre that correspond to the dead zone of attention. But why do proximal locations have such a low priority? Such a waiting list structure may have biological significance; perhaps it is useful to explore the complex environment with a series of large-scale shifts of attention since they allow accumulation of information about global (in terms of stimulus hierarchy) objects or formations (such as sky, forest, house, etc.) that have superiority over local objects (flowers, trees, windows, etc.) (Navon, 1977). It is likely that attention passes a relatively large way from one global formation to another. At the same time, it is unlikely that attention stops and stays somewhere between two formations since it is prevented from perceiving both as wholes. This may serve as a hypothetical reason for the low priority of boundary regions in the waiting list of visual search. The dead zone of attention lies somewhere about such regions (but it appears to be biased towards marginal rather than central formation). Another version of the waiting list hypothesis is considered by Bahcall and Kowler (1999), who suggested that shifting attention far away from a previously attended location is a better strategy since it allows the exploration of a completely novel set of stimuli. In contrast, if attention moves to an adjacent location, then two attended sets will overlap and, hence, novel information will not be acquired as effectively. The waiting list hypothesis is schematically presented in Figure 4C.

4. Double shadow hypothesis. This may be considered as an extension of the waiting list hypothesis. More precisely, it combines the waiting list metaphor with gradient models of attentional allocation around the focus. Here, attention is treated as a gradient spotlight that moves between global formations in an order prescribed by the waiting list. As was stated in the previous hypothesis, high priority is given to central objects and a lower priority is given to marginal objects, and this provides better detection and identification of central changes. The gradient spotlight metaphor assumes that attentional resolution declines from focus to periphery. Thus, marginal objects remain shadowed when the centre object is brightened by the spotlight. If attention tends to make large-scale skips across a naturalistic scene, as was proposed by global feature dominance (Navon, 1977), then the focus of attention should distribute at a centre of interest and then far from that centre. Hence, far marginal items are attended by spotlight from time to time. Consequently, locations between centre and far periphery stay shadowed when spotlight is focused on both central and far peripheral locations. That is what may be metaphorically termed as "double shadow". The double shadow hypothesis is schematically shown in Figure 4D.

These four hypotheses about the nature of dead zone of attention will be tested in our future studies.

There are also several other principal issues that should be addressed in further experiments along with the nature of dead zone of attention. First of all, these concern the spatial properties of this dead zone. What shape of distribution does it have? Is it homogenous, or, maybe, gradually decreasing with eccentricity (e.g., Mounts, 2000a; Müller et al., 2005)? What is the spatial extent of the dead zone? Does it depend on the central area size (e.g., Eriksen & St. James, 1986) or not? Or, how does it depend on the properties of marginal objects within a zone: Their size, number, density, etc.? Further experiments should be conducted to properly address these questions.

CONCLUSION

The present experimental study was dedicated to the allocation of visual attention in the search for changes over complex naturalistic visual scenes. It was found that centres of interest are surrounded by regions where rather enduring change blindness is observed. Special manipulations with attentional salience of centrally attended locations revealed that this centre-surrounding pattern is likely due to central attention. This permits to introduce concept of dead zone of attention. Finally several hypotheses were discussed about the origin of dead zone of attention, namely, suppression, figure–ground, waiting list, and double shadow hypotheses. These speculations should be examined in future experiments.

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