30 Selection-for-perception and selection-for-spatial-motor-action are coupled by visual attention: a review of recent findings and new evidence from stimulus-driven saccade control

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Abstract. The topic of this paper is how selection-for-visual-perception (usually identified with visual attention) and selection-for-spatial-motor-action are related. The later process refers to the fact that simple actions such as grasping an object usually imply the need to select one movement target among other potential targets. In the first part of the paper, a theoretical framework for understanding the relationship between selective perception and motor target selection will be introduced, namely the 'Visual Attention Model' (VAM, Schneider 1995). The main hypothesis of VAM is that of a tight coupling between selection-for-perception and selection-for-spatial-motor-action, which is assumed to be mediated by a common visual attention mechanism. Recent behavioral evidence supporting this claim is reviewed in the second part. The basic experimental paradigm (Deubel and Schneider 1996) required subjects to discriminate briefly presented target stimuli while they were preparing a saccadic eye movement or a manual pointing movement. The data revealed a spatially selective (possibly object-specific) coupling of motor programming and visual perception. In the third part of the paper, three new experiments are reported which investigated whether this coupling also holds when the motor action is directed in a stimulus-driven way. A discrimination judgment had to be made about a letter object that was briefly presented during the preparation of a saccade guided by a peripheral cue. All three experiments showed a tight, spatially specific coupling between the intentionally controlled perceptual discrimination and the stimulus-driven saccade programming. Additionally, the third experiment addressed the question of whether this result is the consequence of an obligatory attraction of attention by peripheral cues *per se*. The data show that a nonrelevant peripheral cue attracted attention automatically only when cue and discrimination target appeared in the same hemifield. We conclude that visual attention is not obligatorily coupled to peripheral cues, rather, the spatial relationship between cue and the goal-driven attentional focusing has to be taken into account. Implications of the new findings for theories of attentional control in visual perception and motor action are discussed.

30.1 Selection-for-perception and selection-for-spatial-motor-action are coupled by a common attentional process: the Visual Attention Model (VAM)

The claim that attention processes play a prominent role in visual perception is supported by a large body of evidence from different experimental paradigms (for an overview, see, e.g. Pashler 1997). Only a limited amount of information that is present at the retina can be processed up to the level of 'conscious' availability. For instance, studies of the change blindness paradigm (e.g. Rensink 2000: Simons and Levin 1997) have shown that a very small number of objects from a natural scene can

be monitored for detecting changes. Given this capacity limitation in conscious visual perception, selection processes are required. They have to determine which parts of visual information—taken up within a single eye fixation—are processed up to the highest perceptual level which allows information to be used for action, e.g. verbal report. There is still a controversy as to where and how in the visual brain such selection processes take place (e.g. Allport 1993; Pashler 1997), but the existence of selection-for-visual-perception as a major attentional function is undebated.

A second function of attention refers to the motor action domain and was termed 'selection-for-action' by Allport (1987). The basic idea is that natural environments usually contain many potential targets for motor actions. However, motor actions such as grasping or pointing are usually directed to only one target at a time. Therefore, a selection process is required that delivers spatial information of the intended target object (its location, size, shape, etc.) to the motor system (Neumann 1987) and that decouples information from other objects from motor control (Allport 1987). For instance, imagine you are sitting in a beergarden and you want to grasp your mug among the other mugs on the table. In this case a selection-for-spatial-motor-action process is needed that selects the spatial parameters of your mug (e.g. its location) in order to control the grasping movement.

How are these selection functions, that is, selection-for-perception and selection-for-spatial-motor-action, related? The 'Visual Attention Model' (VAM, Schneider 1995) postulates that both selection functions are performed by one common visual attention mechanism which selects one object at a time for processing with high priority. More precisely, the following assumptions were made (Schneider 1995):

1. Selection-for-visual-perception is carried out within the ventral pathway of the visual brain. The ventral pathway runs from the primary visual cortex (V1) to the inferior-temporal cortex and has been claimed to be the brain structure that computes visual information (color, shape, category, etc.) about what objects are present in the world (Mishkin, Ungerleider, and Macko 1983).

2. Selection-for-spatial-motor-action is assumed to be carried out in the dorsal pathway of the visual brain, originating also in V1 and ending in the posterior parietal cortex. The brain areas in this pathway compute spatial information required for motor action, for instance, the location and size of the object that will be grasped (e.g. Milner and Goodale 1995). The consequence of selecting this spatial information-for-action is the set-up of motor programs towards the selected object. These motor programs can refer to a grasping, pointing, or an eye movement. They do not imply overt execution, rather, a separate control (go-) signal is postulated for that purpose (e.g. Bullock and Grossberg 1988; Rizzolatti, Riggio, Dascola, and Umiltà 1987).

3. VAM postulates a common visual attention mechanism for both selection functions. This mechanism gives processing priority to low-level visual representations in brain area V1 that belong to a single visual object (see also Duncan 1996). As a consequence, the neural activation flow representing the selected object is processed with highest priority for perception and spatial-motor-action in the higher-level ventral and dorsal areas. Within the ventral areas, this selected object is recognized fastest and made available to conscious visual perception. Simultaneously, within the dorsal pathway, motor programs for a grasping, pointing, or saccadic eye movement towards the selected object are set up with the highest priority.

4. The attentionally mediated coupling of selection-for-perception and for spatial–motor action predicts at the behavioral level that, during the programming phase, the preparation of a spatial–motor action binds the perceptual processing system to the movement target and its location. In other words, the perceptual representation of the external world during movement preparation

should be best for the movement target. Vice versa, the intention to attend to a certain object for perceptual analysis should lead to the implementation of motor programs towards this object.

30.2 A review of recent findings: goal-driven programming of saccades and pointing influences perceptual processing

The claims of VAM were motivated by a number of empirical findings at the behavioral and neural level. Specifically, a study by Deubel and Schneider (1996; Schneider and Deubel 1995) can be considered as the key data source. In that study, we investigated the relationship between one class of goal-driven spatial–motor actions, namely saccadic eye movements, and perceptual discrimination in a dual-task paradigm. Basically, subjects had to perform a perceptual discrimination task while preparing a saccadic eye movement. The spatial relationship between the saccade target (ST) and the discrimination target (DT) was systematically varied. More precisely, as a primary task, subjects had to make a saccade as fast as possible to a location indicated by a symbolic cue. The potential saccade targets were three items of a horizontal linear letter string on each side of fixation (see Fig. 30.1, for a similar task). The secondary task measured perceptual performance. Subjects had to report a DT that was briefly presented within the item string and that disappeared before the actual eye movement started, so that perceptual performance was measured during the saccade preparation phase only. ST and DT varied independently within the three possible positions of the string on each side. If visual attention for perception and saccade target selection could be controlled independently, discrimination performance should not depend on the location of the ST. On the other hand, if both selection processes are coupled via a common selection mechanism, then discrimination performance should be best when ST and DT refer to the same object.

The result indeed revealed a high degree of spatially selective coupling. Discrimination performance was good when ST and DT referred to the same object. Discrimination performance for an object that appeared only one degree to the left or right of the ST location, however, was close to chance level. Furthermore, in a second experiment with the same paradigm, conditions for a decoupling of perception and spatial motor programming were improved by keeping the DT position for a block of trials constant and by informing subjects in advance about this location. Again, perceptual performance was best when DT and ST referred to the same object. Moreover, we asked in this study whether the intended or the actual saccade landing location mattered for perceptual performance. The data clearly showed that perceptual processing priority is on the intended rather than on the actual landing position of the saccade.

The claim that saccade programming and selective perception are related is not unique and it has also been supported by other experimental studies (e.g. Hoffman and Subramaniam 1995; Kowler, Anderson, Dosher, and Blaser 1995; Shepherd, Findlay, and Hockey 1986). However, VAM postulates that *any* spatial–motor action towards an object, for instance, a grasping or pointing action, should bind the attentional mechanism in visual perception. We tested this prediction with the same experimental paradigm as described before, but now subjects had to point rather than move their eyes (Deubel, Schneider, and Paprotta 1998). In contrast to a saccadic eye movement, it is less obvious why the preparation of a goal-directed hand movement should also influence perception. The results showed that perceptual performance was again best when manual target and DT referred to the same location and considerably worse in case of spatial noncongruency. In a further series of experiments (Paprotta, Schneider, and Deubel, in preparation) based on a similar experimental paradigm with

a circular arrangement of stimuli we asked whether the coupling of spatial–motor action and perception would still be found if we allowed movements to be become 'automatized'. We provided the opportunity to 'automatize' by having the movements go to the same location in space for a whole block of trials. In case of repetitive pointing movements we found that perceptual performance did no longer depend on the movement target location. However, for repetitive saccadic movements to the same location in space, the dependency of perceptual performance to the movement location persisted. At the mechanistic level, these results imply that the system responsible for manual movements is able to use a stored motor program for action execution, while movements in the saccadic system are always controlled 'on-line', that is, involving selective attention.

Further evidence for the relevance of visual selection processes in movement programming comes from studies by Tipper, Lortie, and Baylis (1992; see also Tipper, Howard, and Houghton 1998), Castiello (1996), and Craighero, Fadiga, Rizzolatti, and Umiltà (1998). Tipper et al. (1992) investigated the effect of a distractor on a reaching movement towards a target. Interestingly, an effect of the distractor on the movement latency was only observed when the distractor appeared between the starting position of the hand and the target location. Distractors beyond the reaching target did not influence the response latency. So, competition between target and distractor for movement control depended on their spatial relationship. Castiello (1996) investigated interference effects of distractors on a grasping movement. In this study, the distractors were task-relevant for a secondary nonspatial task. Given these conditions, Castiello (1996) found an effect of the distractor on the kinematics of the grasp. These interference effects can be interpreted as behavioral evidence for competition of different objects for controlling the movement. Craighero et al. (1998) investigated whether a non-relevant prime picture influenced the latency of the following grasping movement. They found a reduction of grasping latency when the prime picture depicted the to-be-grasped object, as compared with the condition in which the prime depicted a different object. So, visual perception of an object, here the prime, influenced the programming of a movement that immediately followed the perception. The authors interpreted this finding in terms of the 'premotor theory of attention' (Rizzolatti, Riggio, and Sheliga 1994; Rizzolatti et al. 1987) which will be compared with VAM in the General Discussion section.

30.3 Stimulus-driven saccade control and its influence on visual perception: new experimental evidence

Up to now, all reported studies that found an influence of spatial–motor programming on visual perception concerned intentional, goal-driven movements based on a symbolic cue which required a transformation of the meaning of the cue into a movement target position. The intention to move according to the instruction gave the cue its meaning and its power in controlling the movement. However, movement target selection and the underlying visual attention process can also be controlled in a *stimulus-driven* way (e.g. Jonides 1981; Müller and Rabbitt 1989; Yantis 1998). This means that the stimulus characteristics are able to control the allocation of the attentional mechanism and consequently (according to VAM) also movement target selection. The stimulus characteristics can be related to elementary physical features such as color, shape, and motion. For instance, if a single red circle appears among green circles then it seems to pop out and visual attention is directly allocated towards this singleton. Other ways to attract visual attention in a stimulus-driven way may involve, for instance, abruptly appearing objects (onsets) or moving

objects (see Yantis 1998, for an overview). In many experiments, stimulus-driven control of attention has been realized by peripheral cues (e.g. Jonides 1981; Müller and Rabbitt 1989)—sometimes also called 'direct cues'. These peripheral cues have proven to be efficient in attracting attention in a stimulus-driven, exogenous, and involuntary way (see Müller and Rabbitt 1989; Yantis 1998). In the experiments that we will report in the following the peripheral cue consisted of a abruptly appearing bar marker that appeared directly at the location to which the movement (and therefore attention) had to be directed.

A number of empirical studies have shown that endogenous, goal-driven and exogenous, stimulus-driven control of visual attention and of saccadic eye movements differ in a number of functional characteristics. First, it has been demonstrated that shifts of visual attention have different time courses for peripheral cues and for symbolic cues (e.g. Müller and Rabbitt 1989; Nakayama and Mackeben 1989). Peripheral cues lead to a faster, more transient build-up of processing priority at the attended location compared with symbolic cues. Second, peripheral cues are much harder to ignore than symbolic cues (e.g. Jonides 1981; Yantis 1998). Third, exogenous and endogenous saccade control also differ in important respects. Based on lesions studies and other lines of evidence it has been suggested that different pathways in the primate brain control different types of saccadic eye movements (e.g. Pierrot-Deseilligny, Rivaud, Gaymard, Müri, and Vermersch 1995). Stimulus-driven saccades are claimed to be controlled and triggered by a pathway from V1 via the parietal eye field (LIP in the monkey) to the superior colliculus (SC), while the pathway for intentional saccades involves the frontal eye field that in turn projects to the SC and also directly to the saccade generator of the reticular formation. Given this pathway architecture it is possible that stimulus-driven saccades are triggered independently of intentional saccades. Recent behavioral data by Theeuwes et al. (1998, 1999) indeed suggest that intentional and stimulus-driven saccades can be programmed in parallel; further support for the claim of different pathways of saccade control.

Given these different characteristics of two control forms for visual attention and saccadic eye movement, it is not unreasonable to assume that selection-for-perception and selection-for-motor-action in saccades can be decoupled if one selection function relies on stimulus-driven control and the other on goal-driven control. VAM, however, assumes that decoupling should not be possible despite the different types of attentional control. In order to test which of the two hypotheses holds, we performed three experiments using a similar experimental paradigm to the one introduced above (Deubel and Schneider 1996). This time, however, subjects had to prepare and execute a stimulus-driven saccade directed by a peripheral cue while the secondary task involved goal-driven selective discrimination.

Experiment 1 relied on the same experimental parameters as Experiment 1 of Deubel and Schneider (1996), except that peripheral cues instead of symbolic cues were used for directing the saccade. Experiment 2 was designed to ask whether the coupling is obligatory. In Experiment 3, we introduced an additional fixation control condition in order to the test the widely-held assumption that abruptly appearing peripheral cues attract attention in an obligatory way.

30.3.1 General methods

30.3.1.1 Subjects
Six subjects aged 20–32 years participated in Experiment 1 and 3 and four of these in Experiment 2. All had normal vision and were experienced in a variety of experiments related to oculomotor research. All subjects were naïve with respect to the aim of the study.

30.3.1.2 Experimental set-up

The subject was seated in a dimly illuminated room. Visual stimuli were presented on a fast 21 inch color monitor providing a frame frequency of 100 Hz with a spatial resolution of 1024*768 pixels. Active screen size was 40 by 30 cm; the viewing distance was 80 cm. The video signals were generated by a freely programmable graphics board, controlled by a PC via the TIGA (Texas Instruments Graphics Adapter) interface. Stimuli appeared on a gray background that was adjusted at a mean luminance of 2.2 cd/m². The luminance of the stimuli was 25 cd/m². The relatively high background brightness is essential to avoid the effects of phosphor persistence. Eye movements were recorded with a SRI Generation 5.5 Dual-Purkinje-image eyetracker (Crane and Steele 1985) and sampled at 400 Hz. Head movements were restricted by a biteboard and a forehead rest. The experiment was completely controlled by a 486 Personal Computer. The PC also served for the automatic off-line analysis of the eye movement data in which saccadic latencies, and saccade start and end positions were determined.

30.3.1.3 Calibration and data analysis

Each session started with a calibration procedure in which the subject had to sequentially fixate ten positions arranged on a circular array of 6 deg radius. The tracker behaved linearly within 8 deg around the central fixation. Overall accuracy of the eyetracker for static fixation positions was better than 0.1 deg. Dynamically, however, the eyetracker records considerable artifactual overshoots of the eye at the end of each saccade, which we ascribe to the movement of the eye lens relative to the optical axis of the eye (Deubel and Bridgeman 1995). In order to determine veridical direction of gaze, an off-line program searched the record for the end of the overshoot and then calculated eye position as a mean over a 40 ms time window.

30.3.2 Experiment 1: is there a coupling between stimulus-driven saccade control by peripheral cues and goal-driven selective visual perception?

Given that stimulus-driven control and goal-driven control of visual attention and of saccadic eye movements differ in a number of aspects (see last paragraph), it is not implausible to assume two independent control structures. Experiment 1 was the first step towards testing this hypothesis, which would predict that DT discrimination should not depend on ST location of a peripherally driven saccade. Subjects had to discriminate a briefly presented stimulus (DT) while preparing a stimulus-driven saccadic eye movement. The saccade was guided by a peripheral, abruptly appearing cue that directly indicated ST within a string of letters.

30.3.2.1 Procedure

Subjects performed four experimental blocks of dual-task trials. A block consisted of 216 experimental trials for which the experimental conditions were selected at random. Figure 30.1 shows an example for the sequence of stimuli of a single trial. Each trial started with the presentation of a small fixation cross at the center of the screen, with a size of 0.15 deg. Simultaneously, two strings of characters appeared left and right of the central fixation, each consisting of five '8'-like characters. The width of each item was 0.52 deg of visual angle, its height was 1.05 deg. The distance between the items was 1.09 deg, with the central item of the five letters being presented at an eccentricity of 5 deg. After a variable delay ranging from 800 to 1200 ms, the ST was indicated by two vertical lines (bar marker) appearing directly above and below one of the items. Simultaneously, the fixation
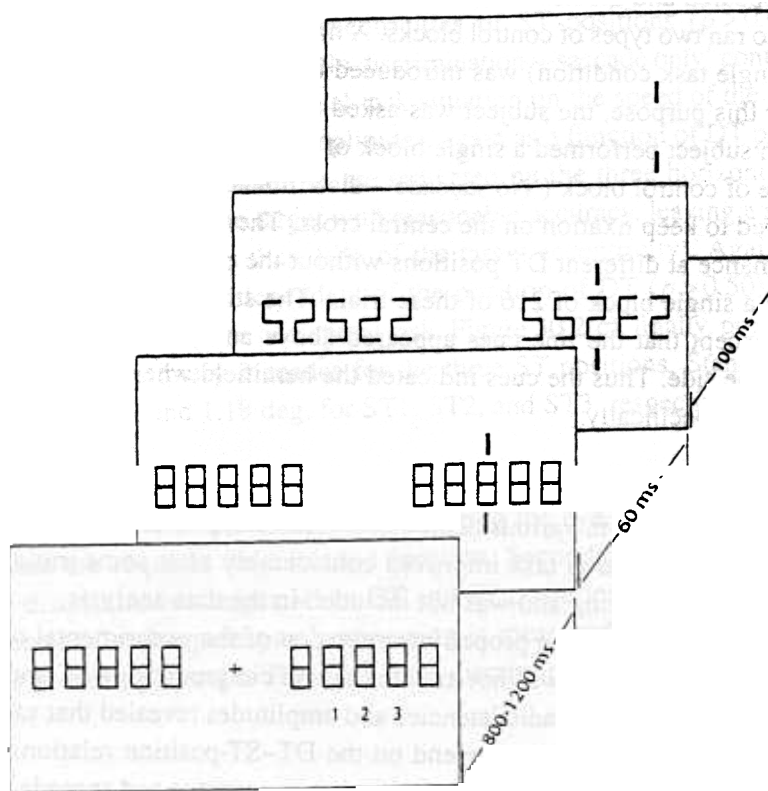
Fig. 30.1   Stimulus sequence in Experiment 1. The subject fixated the central cross for 800–1200 ms. Then a cue consisting of two vertical bars indicated saccade target position. The cue appeared at one of the positions indicated by 1, 2, or 3 in the graph (the numbers are, of course, not shown on the screen), to the left or to the right of fixation. After a delay of 60 ms, the discrimination target and the distractor stimuli were presented for 100 ms. Both distractor and discrimination target disappeared before the onset of the saccade. After the saccade, the subject has to indicate the identity of the discrimination target.

cross disappeared. The side (left or right) and the item position where this cue appeared was varied randomly among the three innermost positions in the string (i.e. at position 1, 2, or 3, as indicated in Fig. 30.1). After a cue lead time of 60 ms, nine of the ten items in both strings were replaced by distractors that were randomly selected to be 'S' or a mirror-symmetric 'S'. One of the three inner items on the side indicated by the ST was replaced by the DT that was either 'E' or a mirror-symmetric 'E'. Thus, the ST cue provided a valid indication of the side where the DT would appear, but did not specify the position of DT within the string. All experimental conditions occurred with equal probability. DT and the distractors disappeared after a presentation time of 100 ms. Consequently, the discrimination target was no longer available 160 ms after the onset of the saccade target. As a result of this stimulus timing most saccades were initiated well after the disappearance of target and distractors. In order to eliminate occasional responses that occurred too early, the off-line data analysis discarded saccades with latencies shorter than 160 ms. Also, in this and the following experiments, trials with primary saccades smaller than 2 deg were not considered in the analysis. This occurred in less than 4% of the trials. After the saccade the subject had to indicate, without time pressure, the identity of the discrimination target by pressing one of two buttons. The two vertical

lines indicating ST stayed on the screen for 2 s until the end of the trial. After that, the central fixation cross reappeared and the next trial was initiated by the computer.

Each subject also ran two types of control blocks. A first type of control block ('No discrimination—saccade only'—single task condition) was introduced to discern saccadic reaction times in a single task situation. For this purpose, the subject was asked to saccade to the ST, but was not required to discriminate. Each subject performed a single block of 216 trials.

In a second type of control block ('No saccade—discrimination only'—single task condition), the subject was required to keep fixation on the central cross. The purpose of this block was to measure perceptual performance at different DT positions without the preparation of an overt saccade. Each subject performed a single block of 216 of these trials. The stimulus sequence was identical to that described before except that the line cues appeared above and below, simultaneously at all three item positions on one side. Thus the cues indicated the hemifield where DT would appear but it did not indicate one item specifically.

30.3.2.2 Results and discussion

Our subjects were experienced in various oculomotor tasks and produced fast and accurate saccades. Performance in the discrimination task improved considerably after some initial practice. The first block therefore served for training and was not included in the data analysis.

One important prerequisite for the proper interpretation of the experimental results was to establish that the saccadic performance was not affected by the congruency of ST and DT, that is, by the perceptual task. An analysis of saccadic latencies and amplitudes revealed that saccadic performance (latency and amplitude) did indeed not depend on the DT–ST-position relationship. Figure 30.2(a) shows saccadic latency (defined as the time between cue appearance and saccade onset) as a function of the position of the discrimination target, separately for the three saccade target positions and averaged over the subjects. Analysis of variance (ANOVA) with repeated measures confirmed that saccadic latency was indeed independent of DT position ($p > 0.20$), with a slight but not significant
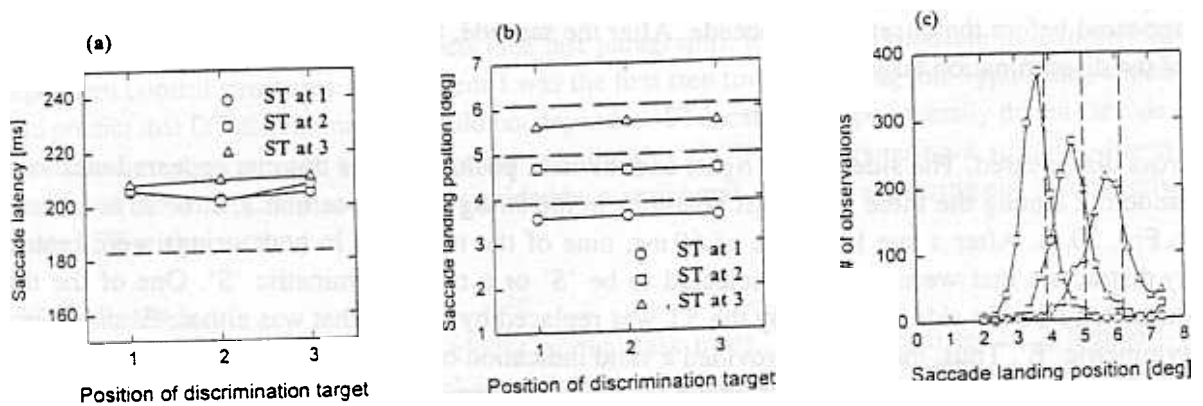
Fig. 30.2 (Experiment 1) (a) Saccadic latency as a function of discrimination target (DT) position (in degrees of visual angle), given separately for saccades directed to the three saccade target (ST) positions. The horizontal dashed line is saccadic latency in the 'No discrimination' control condition. (b) Mean saccadic landing positions as a function of DT position. (c) Distribution of saccadic landing positions for the three ST positions. The dashed lines in (b) and (c) indicate the respective ST positions.

tendency to become longer with larger eccentricities of ST positions ($p > 0.05$). Mean saccade latency was 206 ms. Saccadic latency in the 'No discrimination—saccade only' control task was 185 ms, indicating a general slowing effect of the dual-task situation on the speed of the saccade initiation.

Figure 30.2(b) displays mean saccadic amplitudes, again as a function of DT positions, and for the three ST positions. The actual ST positions are indicated by the three horizontal dotted lines. The graph reveals that the saccades hit the target with reasonable accuracy, leaving a saccadic undershoot in the range of 0.3–0.4 deg (i.e. less than 10% of the target eccentricity). Again, it is important to note that saccadic amplitude was independent of the position of DT ($p > 0.50$), indicating that the saccade accuracy is not affected by the perceptual task. Figure 30.2(c), finally, provides the distribution of landing positions of the primary saccades for the three ST positions. Standard deviations of the end positions were 0.76, 1.1, and 1.18 deg, for ST1, ST2, and ST3, respectively, showing an increase with increasing amplitudes.

Secondary corrective saccades followed with a frequency of 58% of all trials. These follow-up saccades are indeed corrective in the sense that they bring the eye, on the average, between the bar markers that indicate the required final fixation location. Secondary saccades were not directed to the location of the discrimination target, when DT and ST positions differed.

In our experiments, selective perceptual processing is measured by discrimination performance. The three diagrams in the upper row of Fig. 30.3 show discrimination performance for the six subjects
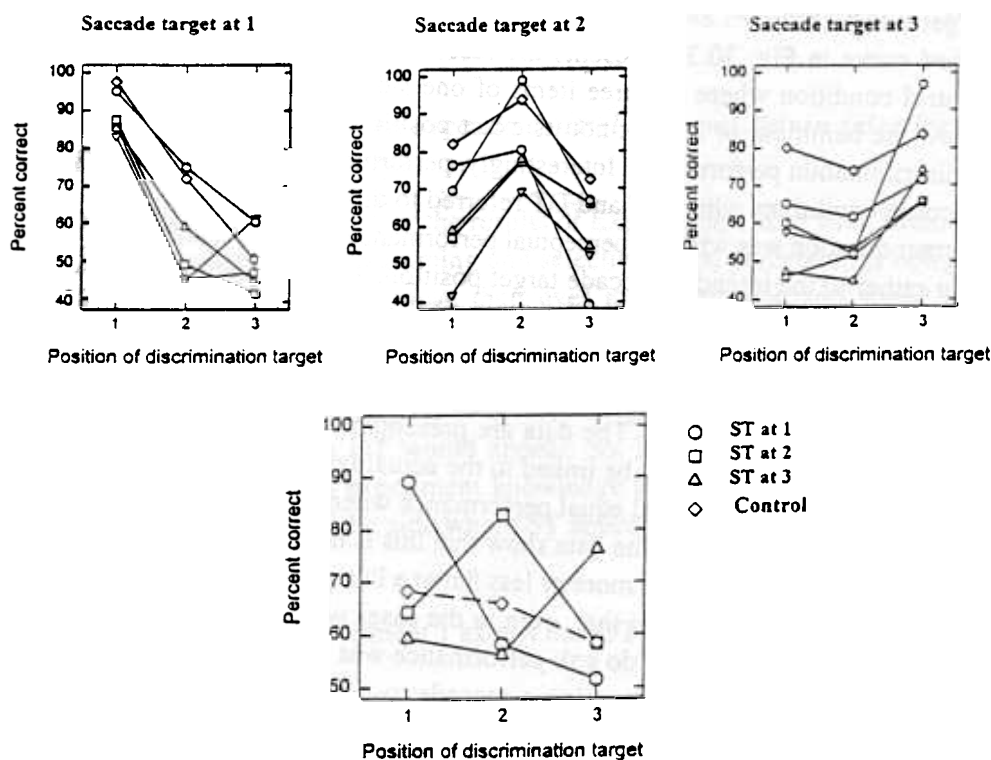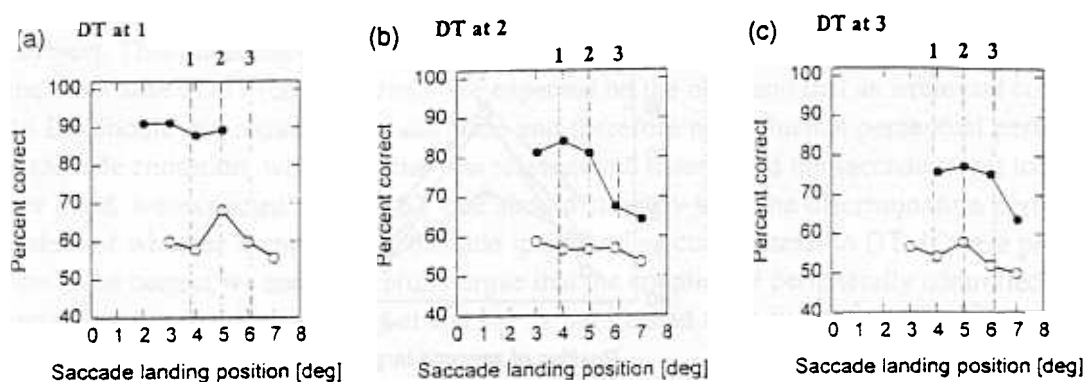

Fig. 30.3   (Experiment 1) *Top row*: Discrimination performance as a function of DT position, given for the saccade cued to ST positions 1, 2, and 3. The data are presented separately for the six subjects. The lower diagram summarizes the data for all six subjects. *Dashed line*: Discrimination performance in the 'No saccade' condition.

who participated in this experiment, measured as percent-correct decisions, and given as a function of DT position. The graphs present the data for the saccade cued to position 1, 2, and 3, respectively, averaged across left and right side of the fixation. It is immediately obvious that performance consistently depends on the relation between position of the discrimination stimulus and the location of the indicated (future) saccade target position. For all subjects and all ST positions, performance was best when ST and DT positions coincided. When the saccade was not directed to DT position, performance decreased steeply and approached chance level. Superimposed on this pattern is that discrimination performance declines from the more foveal to the more peripheral DT locations, that is, from DT1 to DT3.

The lower diagram of Fig. 30.3 summarizes the data across all subjects. For ST1, discrimination performance was close to perfect (88%) when the DT was presented at the ST location, but dropped to 58% at DT2 and finally to the 50% chance level for DT3. This astonishing difficulty in identifying DT if spatially separate from the ST location is also obvious for ST2. In this case, discrimination accuracy dropped from 83% at DT2 (congruency case) to 64% at DT1 and 59% at DT3. A similar data pattern is found for saccades directed by the peripheral cue to ST3. ANOVA (repeated measures) confirmed a highly significant interaction of ST and DT positions, $F(4,20) = 27.2$, $p < 0.001$, and a significant effect of DT position, $F(2,10) = 5.0$, $p < 0.05$. The data show that the ability to discriminate between objects in a multi-object scene during the preparation of a peripherally cued saccade is spatially limited to one common object, the saccade goal. This means that the predicted coupling between selection-for-spatial-motor-action and selection-for-perception holds also when the movement target is determined in a stimulus-driven way by a peripheral cue. In other words, Experiment 1 provides no evidence that goal-driven selection-for-perception can be decoupled from stimulus-driven saccade target selection.

The dashed curve in Fig. 30.3 represents the results of the 'No saccade—discrimination only' fixation control condition where all three items of one side were simultaneously cued. Therefore, subjects knew the hemifield of DT but not its exact position. The data show a low and positional-unspecific discrimination performance. Interestingly, performance is generally superior to the results from the saccade conditions where ST and DT referred to different items.

An important question was whether perceptual performance is linked to the actual landing position of the eye or rather to the intended saccade target position. The relatively broad distributions of the saccade amplitudes as shown in Fig. 30.2(c) allowed for a dissociation of these two aspects. Figure 30.4 provides discrimination performance as a function of the actual saccadic landing positions, given separately for the cases when DT and ST positions coincided (filled circles) and when ST and DT positions differed (open circles). The data are presented for the three DT positions in separate diagrams. If best performance would be linked to the actual landing position of the eye, both curves (filled and open circles) should reveal equal performance when the eyes landed on the DT positions, no matter whether intended or not. The data show that this is not the case. First, the curves when ST positions were different from DT are more or less flat at a low performance level, independent of the actual saccade endpoints. This means that, even in the cases where the eye actually went to land on the DT position (but intended not to do so), performance was close to chance level. Second, for the cases where ST and DT coincided, making a saccade to an item far from DT did not deteriorate performance. So, even when the eyes landed on position 1, the discrimination target at position 3 could be identified accurately given the saccade is cued to position 3. A two-factorial ANOVA, repeated measures, confirmed these conclusions. The first factor determined whether ST position was equal to DT position or not, and the second factor was whether the eye landed on the amplitude

Fig. 30.4 (Experiment 1) Discrimination performance as a function of the actual saccadic landing positions, given separately for the cases when DT and ST coincide (filled circles) and when ST and DT positions differ (open circles). The data are presented for the three DT positions in separate diagrams. The dashed lines in (b) and (c) indicate the respective ST positions.

bin before, at, or after the DT position. The analysis indeed revealed a highly significant effect of coincidence of intended ST and DT position, $F(1,5) = 112$, $p < 0.001$, but a nonsignificant effect of landing position ($p > 0.70$). Also, the interaction was nonsignificant ($p > 0.05$). These results emphasize the importance of the intended as compared with the actual landing position for controlling attention and perception.

30.3.3 Experiment 2: stimulus-driven saccade control and goal-driven selective visual perception: is the coupling obligatory?

An evident question as to the generality of the results of Experiment 1 is to what extent the coupling between stimulus-driven saccade programming and selective visual perception is obligatory, that is, whether subjects are indeed unable to move their eyes to one location and attend to another. In Experiment 1, subjects did not know the position of DT because it could equally likely appear at all three positions inside the string on the side of ST. Therefore, subjects had no incentive to shift their selective perceptual processing away from the intended ST position. However, this incentive should be stronger if subjects knew where DT would appear. So, in order to improve the conditions for decoupling we gave subjects in this experiment knowledge about the position of DT by presenting DT always at the central position of the side where ST appeared.

30.3.3.1 Procedure
The experiment was identical to Experiment 1 except that DT always appeared at the central position of the string that contained ST.

30.3.3.2 Results and discussion
The basic parameters of the saccadic responses were similar to Experiment 1. Mean saccadic latency was 240.5 ms. ANOVA proved saccadic latencies to be dependent on ST position, $F(2,8) = 5.91$, $p < 0.05$. Saccadic accuracy was again high; mean saccade sizes were 3.61, 4.67, and 5.65 deg for ST 1, 2, and 3, respectively. ANOVA (repeated measures) confirmed a significant main effect, $F(2,8) = 206$, $p < 0.001$.
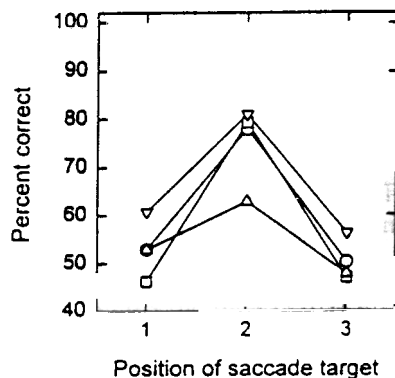
Fig. 30.5   (Experiment 2) Discrimination performance of 4 subjects as a function of saccade target position. The discrimination target was always presented at the central position (DT 2).

The dependence of discrimination performance on indicated saccade target position is shown in Fig. 30.5, separately for the four subjects. Although subjects differed in their overall performance level, it is obvious that preknowledge about test stimulus position did not improve performance at the uncued locations: discrimination rate was still superior when DT and ST coincided, and dropped drastically at the adjacent positions. The main effect of ST position on discrimination performance was significant, $F(2, 8) = 16.5$, $p < 0.01$. The data show that, despite improved conditions for decoupling saccades from selective perceptual processing, there is again a clear coupling of both selection functions.

30.3.4 Experiment 3: optimal conditions for decoupling and the question of involuntary attention attraction by peripheral cues

One may object against Experiment 2 that conditions for decoupling were still not optimal. The fact that DT always appeared at the central position at the side of ST might not be a sufficiently efficient way to provide usable knowledge of the DT position. The time from appearance of the ST cue to the appearance of the DT was only 60 ms, possibly too short to allocate visual attention to the location of the DT. This problem was addressed in Experiment 3 by keeping the DT position constant for a block of trials. Thus, subjects knew that, within a block, DT would always appear at the central position (position 2, see Fig. 30.1) of one side (e.g. left side), so that visual attention in perception could be allocated onto DT position prior to the appearance of ST. This condition should be ideal for a decoupling of selection-for-perception from selection-for-motor-control.

A second issue we wanted to address with Experiment 3 referred to the question of whether an abruptly appearing peripheral cue necessarily binds visual attention in an obligatory way (see Yantis 1998). This would imply that a peripheral cue should always attract attention, independent of whether it is irrelevant (i.e. should be ignored by the subject) or it is relevant as a cue for a saccade. A possible approach to this question is to create an experimental condition where irrelevant peripheral cues per se have a low probability of attracting attention. We reasoned that this situation might be given when peripheral cues appear on the side contralateral to the discrimination target. These cues might be easier to ignore than cues on the same side and in close spatial proximity to the DT. To test these assumptions we introduced an additional fixation condition were the subject was asked

to keep strict central fixation. Nevertheless, a peripheral cue was presented which should be ignored by the subject. This onset cue could appear with equal probability on the same side as DT (ipsilateral) or on the other side as DT (contralateral). We expected on the one hand that an irrelevant cue contralateral to DT should not attract visual attention and therefore not influence perceptual performance. For the saccade condition, where the cue was relevant and determined the saccade target location, on the other hand, we expected that the ST cue should strongly bind the discrimination performance, independent of whether it appeared at the side ipsilateral or contralateral to DT. If these predictions turned out to be correct we could forcefully argue that the coupling of peripherally controlled saccades and perception was not due to the onset cue *per se* but instead to its functional meaning for saccade control.

30.3.4.1 Procedure

The experiment was identical to Experiment 2 except that DT always appeared at the central position of the string (position 2, see Fig. 30.1) at one predetermined side for a block of 48 trials. Within such a block (selected at random), in half of the trials, ST appeared at the same side as DT (ipsilateral), in the other half of the trials, ST appeared contralateral to DT. Subjects performed a total of 4 sessions of a saccade condition and 4 sessions of a fixation condition. Each session consisted of 2 blocks with DT at the left side and 2 blocks with DT at the right side. In the saccade condition, subjects were asked to saccade to ST. In the fixation condition, subjects were told to ignore the peripheral cue and to maintain fixation. Moreover, each subject performed a further control condition of one block of 216 trials where no cue was given.

30.3.4.2 Results and discussion

Figure 30.6(a) shows mean saccade landing positions as a function of the ST position. ST positions contralateral to the side where DT appeared are shown as negative numbers, those ipsilateral as positive numbers. A considerable undershooting behavior is obvious for all target positions, most notably for the ipsilateral position peripheral to DT (position 3). The saccade latencies are shown in Figure 30.6(b). Saccades to the ipsilateral side, that is, to positions +1, +2, +3, are faster than contralateral saccades, that is, to positions −1, −2, −3. ANOVA (repeated measures) reveals a significant effect of the factor 'side' (contra- vs. ipsilateral) on the latency, $F(1, 5) = 15.19$, $p < 0.05$, but no effect of the factor 'cue position within string' (1, 2, 3, that is, inner, middle, and outer position, $p > 0.90$) and no significant interaction ($p > 0.40$). This contralateral slowing reflects the only case in our experiments in which the DT position interferes with the saccade programming. This suggests that the presence of a DT at a blockwise constant position introduces an attentional bias to give more priority to objects and location on the side of DT as compared with the other side.

Figure 30.7 presents discrimination performance. For the saccade condition (open circles) there was no significant effect of the factor 'side' ($p > 0.05$), but a significant effect of 'cue position within string', $F(2, 10) = 33.45$, $p < 0.001$, and of the interaction $F(2, 10) = 10.42$, $p < 0.01$. A further ANOVA (repeated measures) confirmed a significant effect for the factor 'absolute cue position' (−3, −2, −1, +1, +2, +3), $F(5, 25) = 8.64$, $p < 0.001$. Newman–Keuls tests (significance level always 0.05) revealed that performance at the central, ipsilateral ST position (the DT position) was significantly different from all other positions. So, again discrimination is best when ST and DT coincide, implying that preknowledge of DT does not allow to withdraw perceptual processing priorities from the ST.
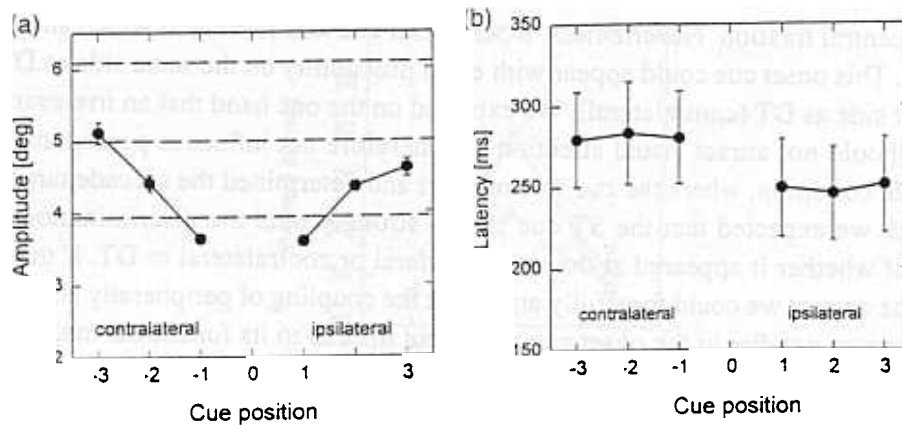
Fig. 30.6 (Experiment 3) (a) Saccade amplitude as a function of ST position. (b) Saccadic latency as a function of ST position.

An important question is whether this coupling of perception and action is due to the peripheral cue *per se* or to the function of the cue for saccade control. The fixation condition was introduced in order to answer this question. If the cue that has to be ignored in this condition attracts visual attention independent of its function for saccade control, the same effect of cueing on perceptual performance as in the saccade condition should be found. The data depicted in Fig. 30.7 show that this is clearly not the case. Performance in the contralateral case of the fixation condition turns out to be different from the saccade condition. For the fixation condition (filled circles in Fig. 30.7) there was a significant effect of the factors 'side', $F(1,5) = 9.90$, $p < 0.05$, 'cue position within string', $F(2,10) = 20.21$, $p < 0.001$ and of the interaction, $F(2,10) = 8.74$, $p < 0.01$. A further ANOVA (repeated measures) confirmed a significant effect of the factor 'absolute cue position', $F(5,25) = 12.04$; $p < 0.001$. For the ipsilateral side, performance at the central ipsilateral position (position +2) is significantly better than performance at positions +1 and +3 (Newman–Keuls). Most importantly, for the contralateral side, there is no reduction of discrimination performance due to the irrelevant cue as compared with the condition where no cue at all appeared (Newman–Keuls), while there is a reduction at position +1 and +3 as compared with the no-cue condition (Newman–Keuls).

Our results show that whether an irrelevant, abruptly appearing peripheral cue influences perception is critically dependent on the *spatial relationship* of the cue position and the intended attentional position. If an irrelevant cue appears on the same side as the to-be-attended target and in close spatial relationship, the cue exerts an unavoidable interfering effect on perceptual processing of the target—stimulus-driven allocation of attention to the irrelevant cue cannot be avoided. However, if the irrelevant cue appears on the side contralateral to the discrimination target, it no longer affects its perceptual processing—stimulus-driven allocation of visual attention can now be suppressed. This has, to our knowledge, not yet been reported in the literature on stimulus-driven attentional control (e.g. Yantis 1998).

While our results show that an onset cue *per se* does *not* necessarily attract attention, a peripheral cue *serving as a target for a saccade* always binds cue position and perceptual processing. This implies that the coupling found in the saccade condition is due to the function of the cue for directing the saccade. So, even for stimulus-driven saccades, the coupling between saccade target selection and selection of the discrimination target is obligatory and restricted to one common target location,
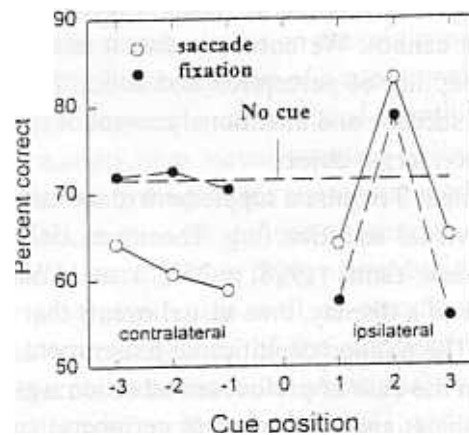
Fig. 30.7 (Experiment 3) Discrimination performance as a function of cue position. The discrimination target (DT) appeared always at position +2. Open circles depict the saccade condition in which the peripheral cue directed the saccade. Filled circles depict the fixation condition in which the cue was irrelevant for the task and had to be ignored.

which argues against the existence of two independent selection mechanisms for stimulus-driven saccade target selection and goal-driven perceptual selection.

30.4 Attentional processes in visual perception and spatial motor programming: general discussion

In this section, we will first summarize and discuss the data of the three experiments. The guideline question will be how selection in perception and selection in spatial–motor action are related when goal-driven and stimulus-driven forms of control are involved. Next, implications of Experiment 3 for the role of space in the issue of stimulus-driven attention will be discussed. Finally, reference will be made to two theoretical frameworks for understanding the coupling of selection processes in perception and action, namely to VAM and to the premotor theory of attention.

Previous studies (e.g. Deubel and Schneider 1996; Deubel, Schneider, and Paprotta 1998) have shown that selection in visual perception and selection in spatial–motor actions are coupled to a common target object when both selection processes rely on intentional, goal-driven control. The new issue addressed here is whether this coupling still holds when spatial motor selection is under stimulus-driven control. The data from Experiment 1 and Experiment 2 clearly demonstrate that peripheral cues for saccade control generate a spatially selective coupling of discrimination performance and eye movement programming, even when subjects are provided with knowledge about the future DT position. In all conditions, discrimination performance was better when DT and ST referred to the same object as compared with the noncongruent cases. In Experiment 3, DT position was kept constant for a block of trials so that subjects could in advance (prior to ST appearance) allocate their perceptual attention directly to DT. Again, performance was by far best when ST and DT referred to the same location and object.

Furthermore, Experiment 3 addressed a central objection against the use of peripheral cues in our experiments, namely the possibility that these cues could attract visual attention in an obligatory

manner—irrespective of the fact that these cues are used for saccade control. The data show that irrelevant contralateral cues can be ignored in visual processing, but that contralateral cues that are relevant for saccade control cannot. We conclude that it is not the abrupt appearance of the cue *per se* that generates the coupling of perception and action but its function to direct the saccade. Stimulus-driven control of a saccade and intentional control of selective visual perception are always spatially coupled to a common target object.

The findings from Experiment 3 require a supplement to the current view on the effects of irrelevant onsets on the allocation of visual attention (e.g. Theeuwes 1995; Yantis 1998) with respect to the role of space. In a recent review Yantis (1998, p. 252) wrote: 'When an observer directs attention to a spatial location in advance of a display, then visual events that would otherwise capture attention will generally fail to do so.' The fixation condition of Experiment 3, however, reveals that attentional attraction by abrupt onsets in the case of prefocused attention was dependent on the spatial relationship between the attended object and the irrelevant peripheral cue—only if both were in the same hemifield was perceptual performance strongly affected by the onset cue. It is an open question for further research whether hemifield crossing or absolute distance between attended object and irrelevant onset cue are the decisive parameters for modulating the interference effect of the irrelevant cue on perceptual analysis.

How general are these conclusions? It still remains to be investigated whether stimulus-driven perceptual selection and goal-driven motor selection would also be obligatorily coupled (as VAM would predict). Moreover, it should be considered that our stimulus-driven saccades were *voluntary*, in the sense that the subject's intention was to use the cue. This is emphasized by the results of the fixation condition of Experiment 3. Peripheral cues that had to be ignored at the contralateral side had no effect on perceptual processing. Therefore, the intention to use the cue for saccade control is decisive for generating the coupling of perception and action. So, 'stimulus-driven' could be defined in the sense that the cue itself (the abrupt onset) allows a direct specification of the motor response, without any further symbolic instruction-based transformation of the cue content. Finally, the saccades in our experiments were 'conscious' in the sense that subjects were aware of their motor action. It is an open question whether the coupling will still be found when the stimulus-driven saccades are involuntary, reflexive reactions that are not noticed by the subject. We have preliminary evidence that this type of reflexive saccade can be programmed without the involvement of visual attention (Mokler, Deubel, and Fischer 2000).

What are the implications of our findings for models of selective perception and motor target selection? Both VAM and the premotor theory of attention indeed postulate an obligatory link between motor programming and attention control. The basic suggestion of the premotor theory is that spatial attention is controlled by motor programs. In its original form (Rizzolatti *et al.* 1987), only saccadic eye movement control structures were considered to direct spatial attention. In its more recent form (Rizzolatti *et al.* 1994), other premotor structures, called 'pragmatic maps' (e.g. for arm movement control), have been claimed to be in charge of attentional control as well. Therefore, the effects of spatial–motor programming on perception as reported above are also compatible with the premotor theory.

Given these common features, the question arises as to what the main differences are between the premotor theory and VAM. First of all, VAM is in one respect more specific than the premotor theory, in that it predicts an *object-specific* coupling between perception and spatial motor programming. No investigations are yet available that have directly studied this aspect—the high spatial selectivity of discrimination performance we found is a hint for object-based selection, but no proof. Movement

programming to overlapping objects may allow us to test whether the object-specificity claim is valid. Second, the theories differ in their assumptions on the origin and the flow of attentional control (see e.g. Chelazzi and Corbetta 2000, for the concept of a attentional control signal). In short, VAM assumes that motor programming is a *consequence* of visual attention processes while the premotor theory claims just the opposite, namely, that visual attention *follows* motor programming. To be more precise, VAM implies that the control signal for attentional modulations of stimulus processing originates in those brain areas that code the task-defined or stimulus-driven selection attributes. The control signal then propagates via V1 to the other higher-level brain areas of the ventral and dorsal streams. In these areas, motor programming as well as conscious visual perceptual perception should occur simultaneously as a consequence of the priorized activation flow from V1. For instance, if a saccade to a red object is to be made, an attentional control signal will originate from the cortical area that codes the color 'red', will flow to area V1, and will spread from there, simultaneously, both to other ventral areas (allowing conscious perceptual report of the red object) and to dorsal motor areas (leading to motor programming). Premotor theory, on the other hand, claims that brain structures responsible for motor programming are the exclusive origin for the attentional control signals—a motor program is always established first, and only then does the attentional signal flow from premotor areas to other parts of brain, implementing spatial attention effects. This control signal flow is not explicitly specified within the premotor theory but it is an evident implication. In order to distinguish these two theoretical options, single cell recordings of the attentional control signal flow might be helpful. If the premotor theory is correct, the control signal flow should always start from premotor areas for programming movements, and attentional effects in the ventral areas should always occur later in time. If VAM is correct, the control signal flow should start in those areas that code the task attributes, and only later should attentional effects occur, simultaneously in other ventral areas responsible for conscious perception and in dorsal areas responsible for motor programming.

A major drawback of the premotor theory of attention and, in part, also of VAM is that neither theory makes very specific assumptions about the attentional mechanisms. They can be considered more as frameworks on the relationship of motor programming and perception than as detailed theories specifying attentional processes at the mechanistic level. VAM is more specific than the premotor theory (e.g. by specifying parts of the control signal flow in the dorsal and ventral areas of the brain), but the theory is also ignorant of some important issues of conceptualizing visual attention processes. One of those issues is the question of how several task-dependent control signals (e.g. signals related to color and size in a task to 'Search for the red and large square') are combined in order to generate attentional effects—see, for example, Bundesen (1990, 1998) and Wolfe (1994) for theories that make specific assumptions on these central issues. Therefore, to obtain a theoretically more satisfying picture on the relationship between movement target selection on the one hand, and selective perceptual capabilities on the other hand, the frameworks should be combined with a mechanistically specific visual attention theory, such as Bundesen's (1990, 1998) Theory of Visual Attention.

Acknowledgments

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