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Investigating attentional mechanisms underlying feature integration: Evidence from within- and cross-modality behavioral and eye movement studies

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1. Summary

The present work is aimed at contributing to a better understanding of the spatial and temporal mechanisms underlying integration of feature signals within and between sensory modalities under search conditions. Furthermore, it investigates the respective contribution of feature signals in the elaboration of memory for the search context in a complex visual search task.

Chapter 2 presents an introduction to selection and integration of information coming from one or more sensory modality, and discusses recent research on the topic.

Chapter 3 concerns the temporal organization of visual feature integration (color, orientation, and motion), somewhat neglected by current cognitive models focussing primarily on spatial mechanisms of feature integration. To evaluate the relative temporal contribution of feature signals defining the to-be-found object, an adapted version of the visual search paradigm (in which an odd object has to be detected among distractor objects) involving redundantly defined items (i.e., objects differing from their neighbors in more than one feature, e.g., a red vertical bar among green horizontal bars) was used, in which all items are identical at the search display onset and the target item is revealed after feature changes of one of the searched items; feature changes are separated by variable time intervals. This procedure allows using the race model inequality (RMI; Miller, 1986) to differentiate two different integration models. Both assume that feature signals are processed independently and in parallel, but diverge concerning the mechanisms that generate the response associated to the target detection. A first model postulates that redundancy gains, referring to the faster detection of redundantly defined targets (compared to singly defined targets), result from a parallel race of independent signals, whose winner triggers the response (race model; Raab, 1962), whereas an alternative account assumes that both features contribute to the response triggering (parallel co-active model; Miller, 1982). Miller demonstrates that all models postulating a strict parallel processing between features, as the race model (Raab), do not violate the race model inequality. Consequently, a violation of this inequality speaks in favor of a parallel co-active processing of features.

Results of experiments described in Chapter 3 demonstrate that visual features are processed according to a parallel co-active model. Moreover the optimal integration of different pairs of visual features (e.g., color and orientation, motion and color, or motion and orientation) does not necessarily occur when both features change simultaneously, suggesting that different

visual features have not the same processing latency. Further, relative processing times of visual features vary according to the required depth of processing (e.g., in feature detection vs. feature identification tasks). Chapter 4 addresses the same issue at a multisensory level and reveals that visuo-auditory signals are also processed according to a parallel co-active model. Furthermore, visual signals (color) have to change simultaneously or between 20 to 40 ms before auditory signals (frequency) to be optimally integrated. This finding is in line with recent behavioral and physiological results of a shorter processing latency for auditory than visual signals. According to results from Chapter 3 and 4, the fact that both RMI violations are observed in both uni- and multisensory paradigms let assume that features, independently of their sensory origin, are processed in a parallel co-active way.

Chapter 5 focuses on the spatial component of visual feature integration by analyzing eye movements in a feature detection task involving redundantly defined targets. Results support the hypothesis that the control mechanism of the oculomotor system can be based on a spatial saliency signal that seems to be governed by the same dimension-based mechanisms proposed to explain the orienting of spatial attention. According to Wolfe's (1994) Guided Search model, the summation of dimensional saliency signals into an overall saliency representation of dimensionally redundantly defined targets generates a higher saliency peak than a target defined on a single dimension. If the saliency amplitude is correlated to the time needed by eyes to be directed toward the targets, a redundantly defined target should elicit saccades faster than a singly defined target. The results confirmed this hypothesis as saccade latencies for dimensionally redundantly defined targets were shorter than for dimensionally singly defined targets. Furthermore, RMI violations were observed for saccadic latencies, demonstrating that both feature signals contribute to the triggering of the saccade. Results were extended by further experiments showing that only a spatial overlap of both features in the redundant target condition (i.e., a single rather than two separate target items) expedites saccadic latencies. When both features were physically separated redundancy gains for saccadic latencies were abolished.

In Chapter 6 the effect of practice on feature integration was investigated by examining variations of the magnitude of RMI violations throughout four experimental sessions in a singleton feature detection task involving color and orientation targets. Results show that participants need some familiarity with the task for clear evidence of parallel co-active processing to emerge.

Finally, Chapter 7 concentrates on the relative effects of distractor features in the generation of contextual cueing. This effect refers to the reaction time benefit observed when the search context, in which the target is embedded, is repeated throughout the experiment. A recent study (Huang, 2006) showed that changing color of distractors after each experimental block abolished contextual cueing. This result demonstrates that not only the learning of spatial configuration, as initially assumed, but also distractor features seem to contribute to the cueing of the target location. In a series of experiments, I systematically tested the impact of distractor feature changes (for the color, orientation, and size dimensions). Results revealed that the single feature affecting contextual cueing is color, indicating that participants take advantage only from learning distractor colors.

Altogether, these results suggest that the cognitive system uses similar, attentional mechanisms to integrate features within and cross modality, arguing in favor of a supramodal system based on a parallel co-active processing. Further, clear evidence of such processing architecture need some practice to be observable. Finally, the oculomotor system seems to be controlled by similar functional principles.

2. Theoretical background

2.1. Introduction

You are entering the station. Your sole preoccupation is to catch the train that brings you back from your congress in a foreign country. Unfortunately you are a little bit too late and the train is leaving in very few minutes. You can not really hurry because of the crowd due to the rush hour. You are looking for the arrivals and departures board in this unfamiliar place and at the same time trying to catch the few words the unintelligible artificial voice from the loudspeakers is saying in English. Someone shoves you but you cannot really pay attention, because this is not your actual worry. Suddenly your train is announced at the platform number 23. You raise immediately your eyes and notice that you are in front of the platform number 5. The big slalom between all "obstacles" on your way to catch safely your train can begin.

To "survive" in such a situation you must pay attention to some relevant information from your environment and ignore the other ones. For instance, information boards are important for you, but you do not really care about whether there is a library or a snack in the station. The same is true for the voice coming from the loudspeakers (relevant) and the hubbub from the crowd (irrelevant). Then, you have to integrate all these relevant (visual and auditory) stimuli to find your way to the platform. But before being able to integrate this information, it first has to be selected. But how does information selection work? This is possible through what is termed *attention*. "Everyone knows what attention is" (Williams, 1890, p. 403, in Müller & Krummenacher, 2002, p. 120), but nobody can define it clearly. In the present work, attention is assumed to be the capacity to select *and* process relevant stimuli from the environment in order to react to them as efficiently as possible.

2.2. How is information selected?

The first modern investigations about information selection began in the early 50's with Cherry (1953) that wondered how people in a party can have a discussion with someone while following another conversation they are not part of. For this reason, he called this phenomenon the “cocktail party” effect. In other words, he wondered how people can explicitly select information from the surrounding background. To investigate this issue, he designed an experiment in which observers wore headphones through which a different message reached simultaneously both ears (a paradigm termed dichotic listening). Their task was to “shadow” (namely follow) the message of one ear and ignore the other one. His results demonstrated that observers were not able to report the content of the message in the unattended ear. However, some physical features could be discriminated (voice gender, categorization of speaker’s age, etc.). Cherry’s (1953) experiment indicates thus that information seems to be somehow filtered at a certain point of the information processing. This capacity of extracting a specific message from acoustically similar noise is not exclusively human. Aubin and Jouventin (1998) reported that King Penguins can recognize their own baby’s cry among others at about a distance of 8 to 9m, whereas the chick recognizes their call at even greater distances.

Using the dichotic listening paradigm, Broadbent (1954) ran an experiment in which people had to deal with two different messages that have to be both reported. The messages were two series of three digits (6-1-3; 5-4-7) presented synchronously and at the same rhythm in both ears. This task type is called the split-span technique because observers had to split their attention to shadow both messages. Broadbent remarked that observers reported digits as a function of the spatial (6-1-3; 5-4-7) and not temporal order (6-5; 1-4; 3-7). He concluded that observers could not attend simultaneously to both ears (information leading “channels”) and had to switch between them to complete the task. The results led him to postulate the existence of a buffer storing any information for a short time, implicating that observers would minimize the number of switching between ears in order to spare resources allocated to the short-term buffer.

According to these results, Broadbent (1958) developed a model, termed filter model, which conceptualizes the nervous system functioning in divided attention tasks. First, information is picked up by sensory modalities and store into a short-term buffer (as described above). Then, due to the limited capacity of the processing channel, a filter has to select the pertinent information in order to prevent the system from overload. According to this model, all information that does not pass through the filter is irremediably lost.

Treisman proposed an alternative model. In a dichotic listening experiment (Treisman, 1960), participants listened to two different messages, each of them coming from a distinct ear, and were instructed to shadow the message from the same ear for the whole duration of the experiment. After a certain time, both messages switched to the opposite ear. She noticed that most of her observers transferred to the wrong message, and this more likely after the switching. Later experiments (Treisman, 1964a, b) provided further evidence that information of the unshadowed message, as a known foreign language or the number of unshadowed messages, could pass through the filter, because unshadowed information could interfere with the relevant message and reduce repeating accuracy. For this reason, Treisman proposed an attenuation model, in which information goes first through a module that analyzes the physical properties of the message. Then it is selected by a filter that allows it reaching a module called "dictionary". The dictionary analyzes information meaning and stores the probabilities that a word occurs in the normal speech. Contrary to Broadbent's model, the selective filter only diminishes the strength of the unshadowed channel that can potentially activate the dictionary if it is in line with the content of the shadowed channel. Nevertheless, though attenuated by the filter, some words with a particular signification, as participant's name, have enough strength to activate the dictionary.

Treisman's results let Deutsch and Deutsch (1963) assume that selection should occur not at the (early) identification stage but in the later processing leading to the response. In their model, they postulated that any information is processed at a high level and receives a certain level of activation related on their relative importance regarding the task. In a second stage, activation levels compete with each other and information with the largest activation level is selected. If its activation stops, the competition for the selection is rerun.

According to prior cited work, two radically different viewpoints concerning the auditory information selection process stand out. Broadbent (1958) postulates that selection occurs at an early stage of processing, whereas Deutsch and Deutsch (1963) assume that selection occurs rather at a late stage. However, a healthy human being has many other information sources available that have to be also selected. The most investigated one is vision. But is the selection process equivalent for visual and auditory information?

Sperling (1960) showed that we can see more than we are able to report. In his experiments, observers had to report flashed digits and letters displayed on three rows. In the first task, observers had to report as many stimuli as possible (whole report task) whereas, in a second one, they were instructed to report the maximal number of stimuli of a precise row that was cued by an auditory signal after the display offset (partial report task). Results showed that participants showed better performances in the partial report (almost always all letters of the cued row were reported) than in the whole report task (about four to five letters can be reported out of twelve). Based on these observations, Sperling made two main assumptions. First, because of the poor performance in the whole report task, he postulated, as Broadbent for auditory information (1958), the existence of a limited short-term store for visual stimuli. Second, because of the quasi perfect report in partial report condition, all the letters have to be perceived but only the cued ones can be selectively processed (as in the dichotic listening, the cued row corresponding to the shadowed message, Styles, 1998). Like in Broadbent's model of auditory information selection, Sperling's results placed visual selection at an early stage in the information processing.

In the following decade, Eriksen and Eriksen (1974) suggested that the selection process of visual information may occur rather in a later stage. They designed an experiment in which participants had to pull a lever in a certain direction according to the type of a target letter. When this letter was an H or a K, observers had to pull the lever for example to the right and when S to the left. The target could be flanked left and right by three other letters that determined the experimental conditions. Those distractors could be either the same as the target (HHHHHHH), a letter requiring the same response (KKKHKKK), a letter requiring the opposite answer (SSSHSSS), letters looking like the target (NWZHNWZ), or finally letters looking like a target demanding the opposite answer (GJQHGJQ). Furthermore they varied the distance between letters (.06°, .5°, and 1° of visual angle). Their results showed that reaction times were affected by the response compatibility of the distractors. The more the distractors were compatible with the target, the faster is the answer triggered. This effect was called the "flanker compatibility" effect. Because of this interference provoked by distractors, Eriksen and Eriksen suggested that all stimuli have to be processed and, therefore, selection seems to occur in a later stage. Moreover, they found that the flanker compatibility effect is reduced as a function of the distance between target and distractors. They concluded that attention could be seen as a spotlight lighting the interesting part of the display whose beam size can process stimuli only within an array of 1 degree of visual angle. This is comparable to a leader of a band when singing his solo; due to his current relevance, he is the only member of the band which has to be enlightened. Because they do not take part to the song, the other members of the band stay in the shadow. However, the band's leader is very dynamic, and is moving all the time on the stage. The lighting engineer has to follow and anticipate his movements to correctly orientate the spotlight in order to keep him into the light. Can the attentional spotlight be moved as a real spotlight controlled by a lighting engineer?

Posner and colleagues (Posner, Nissen & Ogden, 1978; Posner, Snyder & Davidson, 1980) gave evidence that the attentional spotlight is not fixed and can be orientated toward relevant stimuli - without necessarily moving the eyes. In a series of experiments, Posner et al.'s observers were cued about an information concerning the target stimulus that will appear (i.e., mainly its spatial location, but also its form or its sensory modality). For example, in a location cueing experiment, observers had to indicate whether the target was presented during the trial. The target could appear left or right to the fixation point. Before the target onset, a cue was presented, namely either a "+" sign, or an arrow pointing either to the left or to the right. Arrows indicated with a high validity where the stimulus would appear, and the "+" sign providing no information about the target location (neutral cue). Results showed that participants took the cue into account. Relative to the neutral cue trials, observers indicated faster the target location when a valid cue was displayed, and presented slower responses when the cue was invalid. Those observations were replicated with or without moving the eyes (Posner, Nissen & Odgen, 1978). Posner et al. (1980) made similar cueing experiments but the display contained four possible target locations ordered in a row. At the beginning of each block, two locations were cued, corresponding to the two most likely target positions. Results demonstrated that observers were sensitive to the cue validity only when both cued positions were adjacent. According to these observations, Posner and colleagues concluded that the attentional spotlight's beam could be orientated toward the probable locations of relevant stimuli but they had to be spatially close.

Furthermore, the sensitivity to a particular cue type depends on the task. When the cue indicates either the location or the form of the target, participants were more sensitive to location cues. However, in a cross-modal experiment in which target stimuli could be either visual or tactile, cueing the target location was less effective than cueing the sensory modality of the target. In this case, pre-selecting the sensory system is more favorable than pre-selecting the spatial location for the stimulus detection task (Posner et al., 1978). Finally Posner (1980) proposed two modes of spatial control of attention, an endogenous and an exogenous one. The former implicates voluntary attentional orientation guided by a symbolic cue, such as an arrow (detailed above), and the latter orientated attention reflexively through a salient cue, such as a peripheral flash. Paradigms using exogenous cues provided larger gains and costs according to their validity than endogenous cues. Jonides (1981) affirmed that the difference between these control modes came from their degree of automaticity in the process. An exogenous cue engages an automatic, involuntary attentional orientation, whereas an endogenous cue requires a controlled process of attentional orientation.

Coming back to the above mentioned example of the music band, according to Posner et al.'s (e.g., 1978) results, the lighting engineer can anticipate the leader's movements when he receives reliable cues from him, and orient faster and more accurately the spotlight. However, the next song involves the whole band. The actual beam size of our spotlight is not big enough to enlighten simultaneously all band members. How will the light engineer solve this problem? One technically easy solution is to enlarge the beam size. Is attention also able to enlarge its spotlight size? LaBerge (1983) designed two experimental conditions to investigate whether the spotlight beam could vary in size. A string of five letters was presented in the middle of the display. This string could be a word (or a first name) or a non word (an anagram of the word). Observers were instructed to focus on either the whole word (word condition) or the central letter of the string (letter condition). The manipulation implicated attention had to be more largely spread in the word condition than in the letter condition. After the offset of the letter string, a probe appeared at one of the five letter positions and observers had to press a key when the probe was the digit 7. Results showed that, in the word condition, observers answered to the probe at the same speed for all the five positions, whereas, in the letter condition, a V-shaped curve was obtained. Indeed, the farther the probe appeared from the central position where attention was focalized, the more time was required to answer. Therefore, the size of the attentional spotlight can be tuned depending on the task. According to this view, LaBerge proposed that attention works like a zoom lens whose spotlight's beam can be adjusted regarding attentional needs.

Coming back to the metaphor, the solo is now finished, and, according to LaBerge's (1983) results, the whole group can be enlightened by the same spotlight whose beam diameter was enlarged. Another indication that attention spotlight can encompass more than one position at the time raised from electrophysiological studies. Electroencephalographic signals seem to be only sensitive to a probe appearing at or between two monitored positions (Heinze et al., 1994).

As in auditory attention studies, both positions concerning the (early or late) location of the selection process are also discussed in visual attention. This question was ardently debated through the past fifty years (for reviews, see e.g., Pashler, 1998; Driver, 2001), and remains an actual issue.

Hitherto, information selection was discussed; however, selected information coming from the different senses needs to be integrated to engender a coherent representation of our environment. To recognize your favorite blue pen, you have to associate one particular shape to one color. Neurophysiological studies (see e.g., Gouras, 1972; Livingstone & Hubel, 1988; van Essen & Zeki, 1978) showed that visual signals, like color and shape, take independent pathways to reach the brain, suggesting that visual information is processed in parallel. This question was also addressed in the 60's by Neisser.

Neisser (1964) asked observers to find whether a previewed letter (Z) is present or absent in 25 to 40 lists of four to six letters. Distractors could be either all round (D, G, O, Q, R, S, U) or angular letters (E, I, K, L, M, V, W). Results showed that observers' reaction times depend on three factors, presence or absence of the target, target position in the list, and distractors' similarity with the target. First, reaction time is longer when the target is absent than when present. Second, in target present lists, the more the target is at the bottom of the list, the more time is needed to find it; when the target is absent, the more lists there are, the more time is needed to give the answer. Third, search is easier when the degree of similarity between target and distractors is reduced (Z among round letters). This last observation suggests that when target and distractor letters share some similarities they are bound together and make search harder, but when they are different, no binding is done and the target letter can pop out.

Neisser's (1964) study demonstrates that objects presenting a high degree of similarity are automatically bound together. However, the binding process can malfunction leading to incorrect perceptions, as shown by the report of "illusory conjunctions" by patients and healthy observers. An illusory conjunction is observed when features from different objects are incorrectly recombined into new objects. For instance, a red X and a blue N are flashed and observers reported a red N and a blue X. Treisman and Schmidt (1982) postulated that illusory conjunctions occur when features are correctly identified and additionally attention is overloaded. In their experiment, healthy observers were briefly presented cards with 3 colored letters flanked by two black digits (e.g., 6 T S N 4). They had to primary report the black digits as a number (attention overloading task) and then the position, color and name of the letters. Results showed that participants made more illusory conjunctions than other error types. Further, Treisman and Schmidt found additional evidence that illusory conjunctions are exclusively a problem of binding features.

Feature binding can also break down after brain injuries (Friedman-Hill, Robertson & Treisman, 1995; Bernstein & Robertson, 1997) or as a result from a certain disease (Robertson, Treisman & Friedman-Hill, Grabowecky, 1997). Patient R.M., suffering from a bilateral parieto-occipital lesion, presented illusory conjunctions for two (color and shape) and three features (color, shape and motion; Friedman-Hill et al., 1995; Bernstein & Robinson, 1997). People suffering from a Balint syndrome, characterized by an optic apraxia (inability to fix a peripheral object when seeing and recognizing the to-be-fixed target), an optic ataxia (inability to reach an object under visual guidance) and a simultagnosia (inability to see two objects simultaneously, Gil, 2000) present also illusory conjunctions (Robertson et al., 1997).

2.3. Mechanisms of unimodal feature integration

The fact that feature binding can malfunction provides evidence that features are automatically integrated under normal circumstances. However, it does not explain how features are integrated.

2.3.1. Feature integration models

Cognitive models investigating feature integration mechanisms are numerous, but the present work will focus on three principal ones. All models have in common that each feature is processed by its own independent module. The first model, called *serial process model* (e.g., Grossberg, Mingolla & Ross, 1994; Treisman, 1988), assumes a cognitive architecture organized as a pearl necklace, in which features are processed one after another, implicating that the processing of a feature cannot start after the complete analysis of the preceding one. In this case, object perception occurs only at the end of the processing chain. Derived from this assumption, the processing time for an object should be equal to the summed processing time of each of its features.

However, results obtained in the visual attention literature are incompatible with this prediction. For instance, a target object differing from all others in many features (redundantly; e.g., a red left-tilted bar among green vertical bars) is faster detected than an object defined by only one feature (e.g., a blue vertical bar surrounded by green vertical bars; see e.g., Krummenacher, Müller & Heller, 2001). If target features were serially processed, the processing time for a redundantly defined target should be equal to the summed processing times of color and orientation separately. This boost in reaction times for "redundant" objects was called redundancy gain, or redundancy signals effect (Raab, 1962).

Two models were proposed to explain this accelerated response to redundantly defined targets. The first one assumes that redundancy gains are due to "statistical facilitation" arising as a result of a parallel race of independent signals to trigger a response (race model; Raab, 1962), while the second, alternative account postulates that independent signals feed into a common module that triggers the response. In contrast to a parallel race, both signals contribute to the activation of the response thus the term "co-active" processing model (Miller, 1982). Miller proposed a method for differentiating parallel race and parallel co-active models. Although both models assume that signals are processed independently and in parallel, they diverge concerning the mechanisms responsible for the response triggering. The parallel race model assumes that the response indicating the presence of a target is triggered after one of the signals exceeds a threshold required to trigger the response. Assuming that the reaction time distributions of the single signals overlap and that the faster of the two signals triggers the response, reaction times for redundantly defined objects are *on average* faster than expected based on the reaction time distributions for singly defined targets, producing redundancy gains.

Miller (1982) suggests that the response stems from the summation of the processing activation of both feature signals. When this activation accumulation exceeds a certain threshold, the answer is triggered. He proved that all models postulating a strict parallel processing between features, as the Race Model (Raab, 1962), do not violate the following inequality: $F_R(t) \leq F_{T1}(t)+ F_{T2}(t)$, where t is the time since display onset and F the cumulative function of the reaction times. T1 and T2 correspond to the features composing the redundantly defined object R. Violations of this inequality (labeled as race model inequality, RMI) give therefore evidence against a strict parallel processing and in favor of parallel co-active processing.

2.3.1.1. Visual feature integration and redundancy gain

Given that a serially structured model cannot take account of redundancy gains, a parallel processing seems thus to govern the feature integration. But do all sensory modalities operate comparably? As seen before, illusory conjunctions reported by Treisman and Schmidt (1982) and neurobiological research (for review see Wurtz & Kandel, 2000) raised evidence for a parallel, independent processing of visual features. Furthermore, visual attention literature provides support of redundancy gains for visual objects. Indeed, the onset of two stimuli are faster detected than of a single stimulus, at a manual reaction time level (Grice & Canham, 1990; Miller, Beutinger & Ulrich, 2009, Mordkoff & Miller, 1993; Mordkoff & Yantis, 1993; Mordkoff, Yantis & Egeth, 1990; Reuter-Lorenz et al., 1995; Savazzi & Marzi, 2008; Schwarz & Ischebeck, 1994; van der Heijden, La Heij & Boer, 1983; van der Heijden, Schreuder, Maris, & Neerincx, 1984; Marzi et al., 1996) as well as at an oculomotor level (Turatto & Betta, 2006). A similar observation was made for redundantly defined objects in visual search tasks (Koene & Li, 2007; Krummenacher, Müller & Heller, 2001, 2002a, 2002b; Nothdurft, 2000; Poom, 2009; Zehetleitner, Krummenacher & Müller, 2009). In these tasks, participants have to detect the presence of an odd target object (e.g., a red bar) surrounded by other non-target objects (e.g., green bars). These researchers found that a target differing from distractors in more than one feature (e.g., a red horizontal bar among green vertical bars) was faster detected than a target defined by a unique feature (e.g., a red vertical bar, or a green horizontal bar), suggesting therefore a parallel processing of visual features (such as color, orientation, motion).

Furthermore, violations of the RMI (Miller, 1982) were also observed in visual search tasks (Koene & Li, 2007; Krummenacher, Müller & Heller, 2001, 2002a, 2002b; Poom, 2009; Zehetleitner et al., 2009) and in some of the dual stimuli onset detection tasks (Marzi et al. 1996; Mordkoff & Miller, 1993; Mordkoff & Yantis, 1991; Reuter-Lorenz et al., 1995; Savazzi & Marzi, 2008; Schwarz & Ischebeck, 1994), providing evidence for a parallel co-active processing of visual features.

Further evidence in favor of a co-active parallel processing for visual features is provided by a recent electrophysiological study conducted by Töllner, Zehetleiner, Krummenacher and Müller (in press). They examined whether redundancy gains arise either at an early (feature processing, or pre-attentive), or at a late (response selection, or post-selective) processing stage as claimed by Miller, Beutinger and Ulrich (2009). To determine the exact origin of redundancy gains, they combined mental chronometry (reaction times) with electrophysiological markers that reflect either purely pre-attentive perceptual (PCN), preattentive and post-selective perceptual plus response selection-related (stimulus-locked LRP, sLRP), or purely response production-related processes (response-locked LRP, rLRP). As expected, redundancy gains and evidence for a co-active parallel processing were observed at a manual response level. Moreover, electrophysiological data confirmed that redundancy gains originate from the feature processing stage.

Altogether, these results cumulate a reasonable amount of evidence in favor of a parallel co-active processing for visual signals. But do the other sensory modalities, as audition and touch, share a similar feature processing architecture?

2.3.1.2. Auditory feature integration and redundancy gain

Similarly to visual features, auditory features, as pitch, intensity and localization, seem to be first processed independently before their integration. Indeed, auditory illusions stemming from a malfunctioning in feature integration can be observed. Deutsch (1974) reported the so-called octave illusion. In this phenomenon, two tones separated by an octave were rapidly presented and alternated, namely, each tone being displayed in one ear at the time. When questioned about what they heard, participants reported a lateralization of the pitches and a continuous jump from one ear to the other (e.g., the first tone in the left ear followed by the other tone in the right ear, followed again by the first tone in the left ear, and so on). Furthermore, Hall, Pastore, Acker and Huang (2000) reported auditory illusory conjunctions by musicians. They were asked to indicate the presence or absence of a target sound defined by its pitch and the type of instrument it stems from in a two or four-tone “search array”. Before the onset of the “search array”, one of the three auditory cues was displayed. In the first condition, the cued tone was played in the “search” array (valid condition). In the second condition, the cue was not displayed in the search array (invalid condition), whereas in the last one, each tone in the search array shares one feature of the cue tone (illusion condition). As in illusory conjunctions of visual features, error rate analyses showed significantly more errors in the illusion than in other cue conditions.

These types of illusions raise some evidence that auditory features are processed in a parallel way. Another argument for this point of view is the getting of redundancy gains in reaction times for two tones. Schröter, Ulrich and Miller's (2007) participants showed a faster detection of two tones presented simultaneously one per ear than of a single tone presented either to the left or to the right ear. RMI violations were also reported, but only when the redundant stimulus was composed of a pure tone and a white noise. When two (same or different) pure tones were presented simultaneously, neither redundancy gain nor RMI violations were observed. According to these results, the auditory system has to recognize two tones as two distinguishable entities in order to process them in a parallel co-active way. If two tones are perceived as a single one, they are processed as a single stimulus, abolishing redundancy effect. Altogether, tough less investigated than vision, these findings suggest that auditory features – similar to visual features – are processed according to a parallel co-active processing.

2.3.1.3. Tactile feature integration and redundancy gain

Visual and auditory features appear thus to be integrated according to a parallel co-active processing. Is the somatosensory system governed by a similar processing organization? Biological studies (for review, see Gardner & Kandel, 2000) showed that the somatosensory system consists of a multitude of receptors specialized in one of the modalities of touch, temperature, pain, and limb proprioception. Each of these receptors is connected to specific nerve fibers transmitting in parallel but independently their information to the brain, generating therefore different activation in the brain for a same object (see Philipps, Johnson & Hsiao, 1988). In order to have a coherent tactile perception of this object, all this information has to be integrated in a further stage. As seen before, this type of architecture is favorable to generate illusions. Indeed, an illusory sensation of a strong, often painful, heat can be produced after touching a grill composed of hot and cold bars (Thunberg's illusion; see for example Craig & Bushnell, 1994). This illusion originates from the different reactions to the grill of the receptors which are sensitive to innocuous and noxious cold. Furthermore, similarly to Schröter et al. (2007), two skin stimulations can be perceived as a unique stimulus (Sherrick, 1964). This phenomenon is called "funneling illusion" because the two stimuli are funneled to a not stimulated central location generating a single tactile percept. Using this illusion, a recent optical imaging study (Chen, Friedman & Roe, 2003) reported that the somatosensory cortex (first cortical area receiving somatosensory information) is topographically organized according to the perceived rather than the physical location of the stimulations, as thought before (e.g., Gardner & Kandel, 2000). Further, in a study investigating the uni- and bimodal integration of visual and tactile stimuli, Forster, Cavina-Pratesi, Aglioti and Berlucchi, (2002) observed significant redundancy gains (but no violation of the RMI) for two simultaneously presented tactile stimuli. Finally, faster tactile classification times were observed for objects classifiable by two (redundant) features (i.e., size and form) compared to those by only one feature (Reed, Lederman & Klatzky, 1990).

2.3.2. Spatial feature integration: the map concept

Even if the number of the previously reported studies varies greatly depending on the sensory modality, they give at least biological and behavioral support for a parallel feature processing organization for vision, audition and touch. Furthermore, some piece of evidence speaks in favor of a parallel co-active integration. Although a similar processing architecture for feature integration can be observed in different sensory modalities, it does not explain how feature-based information extracted from a natural scene can help orienting attention toward relevant information. One commonly proposed account is the concept of a feature map representing the different aspects of a specific feature dependent on their location in their sensory-specific, spatial representation.

2.3.2.1. Visual feature map

Following the idea of an early parallel feature process, the feature maps concept (e.g., Koch & Ullman, 1985; Itti & Koch, 2000, for a model implementation) assumes that each feature is processed by detectors topographically distributed among the visual field. Based on detector analysis, a map depicting information about features is generated. This account was first proposed by Treisman and colleagues (Treisman, 1977; Treisman & Sato, 1990) to explain the effect of the context on the detection of a target.

They observed that the time necessary to detect a target object surrounded by homogenous distractor objects (e.g., a red vertical bar among green vertical bars [see Panel A of Figure 2.1]) is not affected by the number of objects in the search display. Phenomenally, the target seems to "pop out" of the display independently of the displayed objects. For this reason, this type of visual search was termed pop-out search; more formally, as the target differs from non-targets in one particular feature, pop-out search is alternatively referred to as feature search. In contrast, when the target was surrounded by heterogeneous distractor objects that shared features with the target object (e.g., a red horizontal bar among green horizontal and red vertical bars; see Panel B of Figure 2.1) the search time increased as a function of the number of display objects. Because the target was defined by a unique conjunction of features, this search type was termed feature conjunction search.

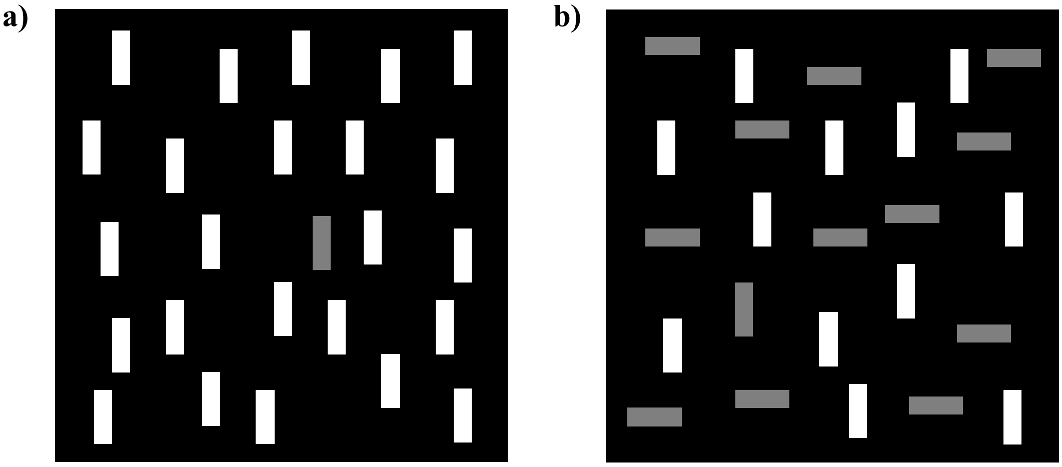

Figure 2.1. **Panel a** displays an example of a pop-out search task and **panel b** an example of a conjunction search task. The white elements stand for the green bars, and the grey elements for red bars. Because it differs from the other bars by its unique feature, the red vertical bar is easier detectable in the panel a than in panel b in which it is the single bar composited of unie feature combinaison.

2.3.2.1.1. Feature Integration Theory

To explain the difference in detection times, Treisman (Treisman, 1977, Treisman & Gelade, 1980) proposed a two-stage model for the visual perception called Feature Integration Theory. In a first step, a master map of locations is generated that depicts the position of all objects presented the visual field. In a second step, attention selects a portion of the master map of locations. Only features under the spotlight of attention are analyzed in parallel by topographically organized feature-specific maps (e.g., red, green, horizontal, vertical, etc.) and then integrated to form a temporary percept of the objects. This percept is then compared to object representations stored in memory. Recognition occurs when the percept matches its representation in the memory.

In a pop-out search task, a target can directly be detected at the parallel feature extraction level because a unique location is activated in a single feature-specific map. In the example illustrated in panel A of Figure 2.1, only the red map will present a single activation. However, this mechanism is not sufficient to detect a target in a conjunction search task because no feature-specific map reports a unique activation. In the preceding example, many objects activate the red-, green-, horizontal-, and vertical-specific maps. For this reason, a serial scanning of the objects has to be engaged, leading to a reaction time increase positively correlated to the number of items in the display.

2.3.2.1.2. Guided Search

Wolfe and colleagues (Cave & Wolfe, 1990; Wolfe, 1994; Wolfe, Cave, & Franzel, 1989) propose a saliency-based model, called Guided Search, which proposes an alternative explanation for the differences obtained in detection and conjunction tasks. In this model, saliency corresponds to the degree of dissimilarity between an object and its neighbors. In contrary to FIT postulating a specific map for each single feature, Guided Search considers features (e.g., red or green, horizontal or vertical) as variations of the same dimension (e.g., color or orientation). The model assumes furthermore that each dimension is first processed by topologically arranged detectors which compute the local difference between dimensional values for the entire visual field and generate local saliency signals that form altogether a saliency "map" for this particular dimension. Saliency signals from the different dimension-specific maps are then summed (or, in other words, integrated) onto a so-called overall saliency map. At this level, the visual scene is represented only in terms of saliency signals intensity. Finally, attention is guided toward the largest saliency peak of the overall saliency map.

In the case of a pop-out search, the target contrasts hugely with the distractors by its color, generating a large signal at one location on the overall saliency map guiding attention directly toward it. In contrary, in a conjunction search, the saliency pattern in the overall saliency map is less clear. Because of their heterogeneous nature, distractors generate additional "noisy" contrast signals, hiding noticeably the contrast signal evoked by the target. Because no location breaks clearly away, each object has to be scanned until the target is found.

Both FIT and Guided Search explain results from conjunction tasks by a stimuli-driven, also termed bottom-up, process in which only visual scene characteristics drive the search. However, when looking for a particular object, we have already some knowledge about it. For example, when searching an orange in a basket of fruits we will focus on orange round objects and deliberately ignore apples, pears and bananas that do not present this specific feature combination.

Taking into account the participants' knowledge about the relevant features of the target, Treisman and Sato (1990) proposed in a revision of the FIT a feature inhibition mechanism that works conjointly with the serial scanning of the visual scene. This mechanism inhibits maps whose features do not define the target and reduces consequently the number of items to be scanned. For example, when it is known that the target is red, all feature maps specific to other colors are inhibited. In the case of a red vertical bar among green vertical and red horizontal bars, only vertical- and horizontal-specific maps will be activated, and, as in a pop-out search, a single map, the vertical one, will present a unique activation.

Although not relying on the same mechanism, knowledge about target-defining features reduces also the number of objects to scan in Guided Search by boosting the contrast signals for objects sharing features with the target. When summed up onto the overall saliency map, the target can emerge more easily from its surrounding, leading to faster detection times. For instance, if it is known that the target is red, the computation of the saliency signal will be biased in favor of the red objects, enhancing the saliency signal intensity for these objects at the overall saliency map level and reducing consequently the number of locations to be inspected.

2.3.2.2. Auditory feature map

Though presenting architectural differences, foundations of both Feature Integration Theory and Guided Search rely on the map concept, namely a spatial organization of the information. This type of organization is supported by biological data demonstrating that the primary visual cortex (first cortical relay in the visual processing pathway) is spatially arranged (see e.g., Wurtz & Kandel, 2000). But is this concept applicable to each sensory modality? For example, neurons of the primary auditory cortex are arranged according to a map coding tone frequencies without their spatial location (e.g., Hudspeth, 2000). According to this cortical architecture, a feature map should not be observable in audition, at least in the acceptations of FIT or Guided Search.

In a recent study, Kayser et al. (2005) investigated this issue and found evidence in favor of a saliency map for the auditory system. In this model, auditory features (intensity, frequency contrast and temporal contrast) are extracted in parallel from sound waves using different filters. The feature maps are then compared on a dimension map, highlighting the suspicious feature peaks. In the last step, the dimension-specific maps are combined, generating an auditory saliency map. The auditory saliency map model, although organized in a comparable architecture to Guided Search, uses another scale for the saliency map. In Kayser et al.'s model, the saliency signal is measured with regard of the time, whereas Guided Search suggests a topographically structured saliency map. As underlined by Kayser et al., the next step for the auditory saliency map model is to integrate the spatial components of sounds.

Visual and auditory research gives thus some support for a supramodal integration process based on feature maps. Although the models do not concord on the architecture underlying feature map generation (feature vs. dimension maps, spatially vs. temporally scaled maps), they all assume that features are processed in parallel and represented on specific maps that are combined in a further step.

Regarding touch (or more generally somaotosensory system), to the knowledge of the author, no research explores the potential existence in this sensory modality of feature maps as in the acceptance of FIT or Guided Search. Nevertheless, because the pathway between sensory receptors and primary sensory cortices seem to be similarly hardwired (see above), a model based on feature maps could be plausibly envisaged for the somatosensory system.

2.4. Time and attention

The feature map concept appears therefore to be a convincing modeling for feature extraction and integration. However, this concept focuses on spatial aspects of feature integration and neglects somewhat its temporal aspects. But time plays and important role in perception and in findings concerning attention. For example, perceiving two distinct flashed frames as a unique one is a matter of timing. Participants of Di Lollo (1980, Di Lollo & Hogben, 1987) faced a virtual 5x5 dots matrix in which a dot was missing. This matrix was decomposed into two frames of 12 apparently randomly positioned dots, each presented for 1ms and separated by a certain time interval (from 10 to 200 ms, depending on conditions and experiments). Participants' task was to indicate the location of the missing dot. They found that the number of localization errors increased with the stimulus onset asynchrony (SOA) between frames.

In the visual attention domain, Müller and Rabbit (1989) explored the time course of both reflexive and voluntary control of attention orientation using the cueing paradigm developed by Posner and colleagues (Posner, 1980; Posner et al. 1979, 1980, see above) by modulating the SOA duration between cue and display onsets. They observed that an exogenous cue, generating an automatic attention orientation, produced rapidly a maximal facilitation (100 to 175 ms) whereas the strongest effectiveness of an endogenous cue appeared later (400 to 750 ms). According to these results, an automatic orienting of attention occurs and vanishes rapidly, whereas controlled orienting takes time to be effective and lasts longer.

One explanation why the effect of an exogenous cue is short-living came from the inhibition of return effect (IOR). Posner and Cohen (1984), with the help of a paradigm combining non-informative cues with SOAs, observed that target detection speed and accuracy depended on the time interval between the cue and display onset. A short SOA produced the best performances (facilitation), whereas a longer SOA deteriorated them (inhibition) (crossover point at 200-300 ms). This suggests that IOR results from the summation of two effects sharing not the same time course. Facilitation disappears as rapidly as it appears, whereas inhibition takes more time to develop. Based on those findings, they argued that IOR might inhibit the attentional orienting toward an already attended location in order to enhance the probability of inspecting new locations. Subsequent research involving an eye movement preparation condition (Rafal, Calabresi, Brennan & Sciolto, 1989) showed that only an exogenous (but not endogenous) cue generated an inhibition of return, suggesting a close link between oculomotor system and inhibition of return. Finally, the crossover point between benefits and cost of this effect increased systematically dependent on the task difficulty (reviewed in Klein, 2000).

Inhibition of return was recently used to give support that an attentional capture effect occurs in an automatic, stimulus-driven fashion (Theeuwes & Godijn, 2002). An attention capture is assumed when an irrelevant singleton object, because of its salient nature, attracts reflexively attention and interferes in the task solution (e.g. Theeuwes, 1991, 1992, 1994). For example, Theeuwes' participants (1992) were asked to indicate the orientation of the line segment enclosed in a green square surrounded by green circles. In some trials, an irrelevant red circle was added to the display, generating a reaction time enhancement in the line orientation discrimination. This task-unrelated object can take various forms, such as color (Theeuwes, 1992, 1994; van Zoest, Donk & Theeuwes, 2004), orientation (van Zoest et al., 2004), or abrupt object onset (Jonides & Yantis, 1988, Theeuwes, 1991, 1994). Von Mühlenen, Rempel and Enns (2005) examined whether a singleton change in the display could produce an attentional capture. In a preview search paradigm (see Yantis & Jonides, 1984), participants were shown a display in which 8-like placeholders were arranged on a virtual circle. After 1000ms, the form of the placeholders changed to reveal the search display. Observers had to indicate by button-pressing if the target letter hidden among distractors was a U or a H. In some trials, an irrelevant color or motion change of one of the displayed item appeared at different time points. This change could occur during the whole placeholders display time, 150ms before, simultaneously, or 150ms after the search display onset. Results revealed that a feature change of a singleton could capture attention only “during a period of temporal calm (p.979)”, namely, briefly before and after the search display onset, giving support to von Mülhenen et al.’s (2005) unique-event hypothesis, assuming that an attentional capture by a feature change can occur only by temporally unique events.

The reflexive (bottom-up) nature of the attention capture is highly debated. Indeed, goal-oriented (top-down) instructions could override attentional capture (Bacon & Egeth, 1994). On this basis, Folk and Remington (1998) suggested that, because of the presence of more than one singleton, the target has to be distinguished from the irrelevant singleton through a resource consuming filter. According to this hypothesis, the reaction time increase is not inducted by the capture of attention of the irrelevant singleton, but by the setting up of this voluntary selection filter. One way to certify whether the singleton really catches attention is to monitor eye movements during such a task. Adopting a preview search paradigm, Theeuwes, Kramer, Hahn, Irwin and Zelinsky (1999) constructed their letter discrimination task in the target singleton in such a way that focal attention was necessary. In other words, participants have to make an eye movement toward the target singleton to solve correctly the task. When an irrelevant additional object appeared abruptly, one third of the eye movements were first directed toward this latter (this phenomenon was termed oculomotor capture). Similarly, van Zoest et al. (2004) asked their participants to make an eye movement toward a defined target included in a rectangular array of identical distractors. When an object with an irrelevant feature replaced one of the distractors, an inverted link between saccade latency (i.e., the time before eyes begin to move) and accuracy was observed: the faster the saccade was generated, the less precise it was. They argued that attention orientation strategies vary across time; short saccade latency was caused by a reflexive stimulus-driven attentional capture, whereas a controlled, voluntary gaze orientation needs more time to be deployed. Similar findings, comparing parameters of eye and joystick movements, were observed by manipulating the presentation time of the target display and by forcing participants to respond in a short time window (Hunt, von Mühlenen & Kingston, 2007).

2.4.1. Temporal feature integration

Previous cited studies demonstrate thus that time and attention are closely linked. Can time have also an influence on feature integration? The time course of feature integration was firstly investigated by neurophysiologists. Moutoussis and Zeki's (1997a) participants faced a display in which green and red squares moved vertically up and down in a continuous fashion. They were asked to indicate if the color red was associated with a downward motion and the green color with an upward motion by pressing a key or another key if they perceived the opposite relation (attributes pairing task). Changes of color and motion direction occurred after a time cycle of the same duration. Color change cycle could be (or not) objectively synchronous to the motion direction change cycle. For instance, in the case of an objective simultaneous change, the squares were green when moving upwards, and red when moving downwards, whereas, in an asynchronous condition, the color could change before or after the motion direction change. Moutoussis and Zeki observed that participants perceived a synchronous color-motion change when motion changed 70-80ms before color. In a following series of experiments using the attributes pairing paradigm (Moutoussis & Zeki, 1997b), they examined the temporal integration of three visual features (color, orientation and motion). Comparing those experiments allowed them to establish a hierarchy of feature processing speed, where color is processed the fastest, followed by orientation and finally motion.

Based on the delay between feature processes and the anatomically separated pathways for the different features (see above), Zeki and colleagues (2003; Zeki & Bartels, 1999) postulated that the processing location of a feature is also its conscious perception location. Each site produces in a temporal and spatial independent way a "microconsciousness" of the feature which it is specialized in. According to this hypothesis, a unified consciousness appears in a later stage by binding microconsciousnesses together. Because microconsciousnesses are thought to be distributed across time and space, a delay between the conscious perception of color and motion occurs. In this view, feature binding occurs in a late, “post-conscious” processing stage.

Although his advantage for color when “competing” with motion observed by Moutoussis and Zeki (1997a, b) could be replicated (Adams & Mamassian, 2004; Arnold, Clifford & Wenderoth, 2001; Arnold & Clifford, 2002; Aymoz & Viviani, 2004; Bartels & Zeki, 2006; Bedell, Chung, Ogmen & Patel, 2003; Viviani & Aymoz, 2001), the study of Adams and Mamassian (2004) found a slower processing time for color than for motion or no difference at all between color and other visual features (Nishida & Johnston, 2002, Viviani & Aymoz, 2001). An exogenous cue can make either feature processing asynchrony reduce (Paul & Schyns, 2003) or completely vanish (Holcombe & Cavanagh, 2008). Moreover, the relative processing time difference between color and motion appears to be modulable. A small angular difference between motion direction changes reduces the color-motion asynchrony (Bedell et al., 2003). Furthermore, it was demonstrated that feature processing speed depends on the task requirements (Adams & Mamassian, 2004; Bedell et al., 2003; Clifford, Arnold & Pearson, 2003). A reaction time task seems to favor motion processing, whereas a perceptual choice task (i.e., indication which feature changed first) facilitates color processing (Adams & Mamassian, 2004). No advantage was observed by a simultaneity judgment task (i.e., indication whether feature changes were synchronous or not; Clifford et al., 2002). Finally, Holcombe and Cavanagh (2001) found a facilitated feature binding process when feature changes occurred at the same spatial location compared to spatially separated positions.

Such studies questioned the idea of a feature integration occurring at a late processing stage, as claimed by Zeki and colleagues (Moutoussis & Zeki, 1997a, b; Zeki, 2003;Zeki & Bartels, 1999). Other contradictory piece of evidence rises from visual search findings. Krummenacher et al. (2001) compared redundancy gain effects of two types of redundant targets defined by an orientation and a color. These targets were defined by the same orientation, but could have two colors (i.e., red or turquoise). Detection times for singly defined targets showed that orientation and red targets were processed at a same speed, whereas turquoise targets needed about 20 ms more to be processed. If feature binding takes place in a late processing phase, redundancy gains and violations of the race model inequality should be larger for tilted targets colored in turquoise than in red. Results argued against this assumption by demonstrating no advantage for the turquoise redundant targets. Because parallel co-active processing was observed for both redundant target types, Krummenacher et al. (2001) postulated that features might already interact in an earlier stage as initially proposed by Zeki and collaborators (Moutoussis & Zeki, 1997a, b; Zeki, 2003; Zeki & Bartels, 1999).

To clarify the locus of feature integration, Schönwälder (2006) adapted Moutoussis and Zeki’s (1997a, b) motion-color pairing paradigm to visual search by setting up feature changes in this latter. In this paradigm, similar to the preview paradigm (Yantis & Jonides, 1984, see above), the target was revealed when features of one element changed. In the first task, Schönwälder’s participants had to detect any change occurring in the display that was composed of moving green bars that followed a horizontal trajectory on the screen. After a variable time, one (color or motion) or both features of a single object changed. In redundant color-motion changes, the feature changes were separated by variable temporal asynchronies. According to the feature process asynchrony hypothesis, the fastest reaction times should be found when motion changes 70-80ms before color. Results argued against this assumption since targets whose features changed simultaneously were detected at best.

However, due to the investigation of a specific feature combination, it could be assumed that these findings could represent a particular case in the temporal integration of visual features. To verify this assumption I extended Schönwälder (2006) paradigm in a series of experiments pairing visual features, respectively color, orientation and local sinusoidal motion. In local sinusoidal motion all objects on the display move horizontally within a small space range in a consistent fashion. The choice of another type of motion permits to observe whether all kinematic aspects of motion are integrated in a similar way. Indeed, it has been showed that motion characteristics can modulate visual perception. For instance, detection time for a color change in moving objects depends on their velocity (Kreegipuu, Murd & Allik, 2006). Furthermore, a static target can be more easily detected among stimuli executing the same motion than when animated by a random motion (Royden, Wolfe & Klempen, 2001). In contrary to Schönwälder (2006), results demonstrated that the optimal feature integration time point varies according to the feature combination (see Chapter 3 for a detailed discussion of the results).

2.4.2. Attentionally and tempora(ri)lly blind

As reported above, changes can easily be detected (Schönwälder, 2006) and capture attention (von Mühlenen et al., 2005). Fast change detection is survival-relevant in the animal world. For instance, when watering, a gazelle watches closely bushes nearby in order to detect as soon as possible some unusual changes that could betray the presence of a predator. Change detection in already explored (and irrelevant) objects can therefore be salutary. Watson and Humphreys (1997, 1998) demonstrated that the so-called "visual marking effect" can be disrupted by changes in old distractors. In their first study (Watson & Humphreys, 1997) participants were confronted to a conjunction search in which a part of the distractors were presented 1000ms before the remaining part of the distractors ("gap" condition). If a target was displayed, it always appeared among the distractors of the second set of search items. Such a conjunction search produced a similar result as a pop-out search, but requires a minimal time interval of 400ms between the two parts of the search display to be effective. It was argued that the location of old distractors can be inhibited within a feature map (similar to Treisman & Gelade, 1980) in order to prioritize the new objects (Watson & Humphreys, 1998, 2000a). This marking of old distractors requires attentional resources (Watson & Humphreys, 1997) and is used when it is task-relevant (Watson & Humphreys, 2000b). A striking point is that visual marking is change-sensitive. A change of form and color (Watson & Humphreys, 2000a) as well as an abrupt stop of motion at the level of old distractors (Watson & Humphreys, 1998), disrupt this effect. These observations provide further evidence that the visual system is tuned to detect changes.

Nevertheless, changes can also easily remain undetectable. Rensink, O'Regan and Clark (1997) investigated participants' capacity to remark a change between two almost identical pictures. This change could consist either in an omission, or a color change, or a location shift of an object of central or marginal interest. Pictures were presented in alternation for a short time. In one condition, each picture was followed by a short blank ("flicker" paradigm), whereas in another condition no blank was displayed. Introducing a blank between pictures led to an enhancement of the number of alternations (and consequently the time) required to detect the change. Furthermore, change detection depended on the degree of interest of the object; the more interesting the object, the faster the change was detected. This paradigm demonstrates that participants can be "blind" to changes. Grimes (1996) noticed that even an important change (as a hat or head exchange) remains undetectable when occurring during an eye movement. In a movie, the disappearance and reappearance of an object as well as a leading actor exchange, stays undetected for most of the participants (Levin & Simons, 1997). This effect can also be observed in a real social interaction situation. Pedestrians were asked by an experimenter for a building direction on a campus (Simons & Levin, 1998). After 10-15 s of conversation, two other experimenters passed rudely between them with a door. During this interruption, the first experimenter exchanged his place with one of the two others that continued the conversation with the pedestrian. Surprisingly, only fifty percents of the pedestrians affirmed to have noticed the change.

Not only changes, but also objects can be missed. In the attentional blink paradigm, participants are shown a series of rapidly presented stimuli followed by a blank and have two tasks to complete: first they had to name the target (a white letter), and in a second time, to indicate whether a probe (the letter X) was displayed (Raymond, Shapiro & Arnell, 1992). It was observed that the detection of the probe was deteriored only when it appeared two or three stimuli after the target. Raymond et al. (1992) argued that this temporally restricted effect is due to the impossibility for the cognitive system to create a representation of a new object (i.e., the probe) before the complete representation of last attended object (i.e., the target). When the probe appeared directly after the target, the identification of the target was not yet engaged and the probe can be detected. However, during the identification process is engaged (when the probe appeared two and three stimuli after the target), the system could not create a representation of the probe, preventing participants to process new stimuli for this brief time interval. Furthermore, Raymond (2006) demonstrated that attentional blink is object-, and not feature-based. A short-lived deterioration of the probe detection was only noticed when the target and the probe had another shape as the distractors. According to previous study, updating the features of an object does not create a new representation for this object.

An object can also stay invisible when attention is focused on another task. In the inattentional blindness paradigm, Mack and Rock (1998) asked their participants to report which arm of a cross was the longest (horizontal or vertical). The stimulus was displayed for 200ms, followed by a mask. After three or four trials, a small (but clearly visible) square was simultaneously presented with the cross, closely to or at the fixation point. When asked, observers were unable to report the unattended stimulus (in 25% to 80% of the cases depending on the experiment). Even a gorilla going through the scene in a movie can be totally ignored when participants were entrusted with a task requiring focal attention (Simons & Chambris, 1999).

2.5. Eye and attention

Whereas previous studies suggest that the visual system is tuned to detect changes, it seems amazing that an obvious object such as a gorilla can be totally overlooked. This observation questions the relation between eye and attention. Is it possible that participants saw the gorilla without consciously perceiving it? Or did the task require such a focal attention that participants did not even look directly at the gorilla? In more formal words, these suppositions question the nature of the link between attentional and ocular foci. Is the attentional focus necessarily at the same location as the ocular focus, or can they move independently?

Assuming that our attention is directed where we look at sounds quite trivial. However, numerous studies observe that eye movements and attention orienting can be dissociated. For example, in the cueing paradigm, reaction time gains or costs associated with the cue validity remain stable even when gaze is kept at a constant location (e.g., Posner et al., 1978, 1980). This finding gave birth to the distinction between covert and overt attention. Covert attention refers to attention orientation without bodily movements, whereas overt attention reflects a visible (bodily) orientation of attention. The fact that you will certainly look back when a strong and unusual noise blows behind you in order to determine what caused this sound corresponds to a behavior involving overt attention. Although the attentional focus seems to be able to move independently of the ocular focus, eye movements, when investigated, are implicitly assumed to have a close link with attention (Wright & Ward, 2008).

Eye movements are generated by three complementary pairs of extraocular muscles attached to each eye (see Panel a of Figure 2.2**).** Contraction of the superior rectus muscle provokes an upward movement, whereas contraction of the inferior rectus muscle a downward movement. The lateral and medial recti muscles are responsible for the horizontal movements and finally the superior and inferior oblique muscles for the rotation of eye-balls (Goldberg, 2000).

Functionally, eye movements are needed to direct the fovea to the object of interest and to stabilize gaze during body movements in order to maintain the fovea on the object of interest (Krauzlis, 2008). The fovea is a small hollow of 0.2mm size situated in the middle of the retina (Tessier-Lavigne, 2000, see Panel b of Figure 2.2). This part of the retinal tissue possesses the highest concentration of cones (photoreceptors sensitive to colors) that can be more directly activated. Contrary to the other parts of the retina, light do not have to go through many neuron layers before reaching the layer of the photoreceptors (see Panel c of Figure 2.2). Furthermore, unlike the extrafoveal part of the retina, each photoreceptor transmits information to a single neuron of the ganglion layer, providing a very small information convergence to foveal optic nerve fibers and therefore preserving details of the visual information. Its specific retinal architecture makes the fovea the most accurate part of the retina, hence the importance of keeping objects on it.

Eye movements fulfill this function through two different principles, gaze stabilization and gaze shifting. Two mechanisms are involved in gaze stabilization (Krauzlis, 2008): the vestibulo-ocular reflex (VOR) and the optokinetic response (OKR). VOR uses information originated from the vestibular system in order to counterbalance head movements, whereas OKR is directly driven by image changes on the retina. Gaze shifting can trigger three different eye movements: a saccade, a smooth pursuit and a vergence movement. A saccade is a rapid, voluntary (i.e., goal-directed or top-down driven) or spontaneous (i.e., stimulus- or bottom-up driven), ballistic movement that abruptly changes the position of the gaze fixation. In this context, ballistic refers to the fact that, once parameters are computed and the initiation signal was sent, a saccade needs no more information to reach its goal with high accuracy, like a canon bullet (Zingale & Kowler, 1987). A smooth pursuit corresponds to a slow binocular tracking of a moving object. Both saccades and smooth pursuit are called versional movements because they implicate a conjugate movement of both eye balls (both lines of sight stay parallel during the movement). Finally, vergence movements are used in order to adjust the meeting point of both lines of sight when the object moves into the third dimension (depth).

Most studies exploring the relation between attention and eye movements concentrated on shifting movements and more precisely on saccades and smooth pursuit (Wright & Ward, 2008). For example, Hoffman and Subramaniam (1995) demonstrated that making a saccade toward an attended (or cued) location is easier than toward an unattended (or uncued) location. They suggested consequently that an attention shift should occur before an eye movement. Similarly, Deubel and Schneider (1996) showed that attention is shifted to the location where the saccade is programmed to land. According to these studies, eye movements seem to follow systematically shifts of attention. For this reason, the attention shift can be envisaged as an "advance scout" (Wright & Ward, 1998), which could generate some spatial coordinates helping to program saccades (Wright & Ward, 2008).

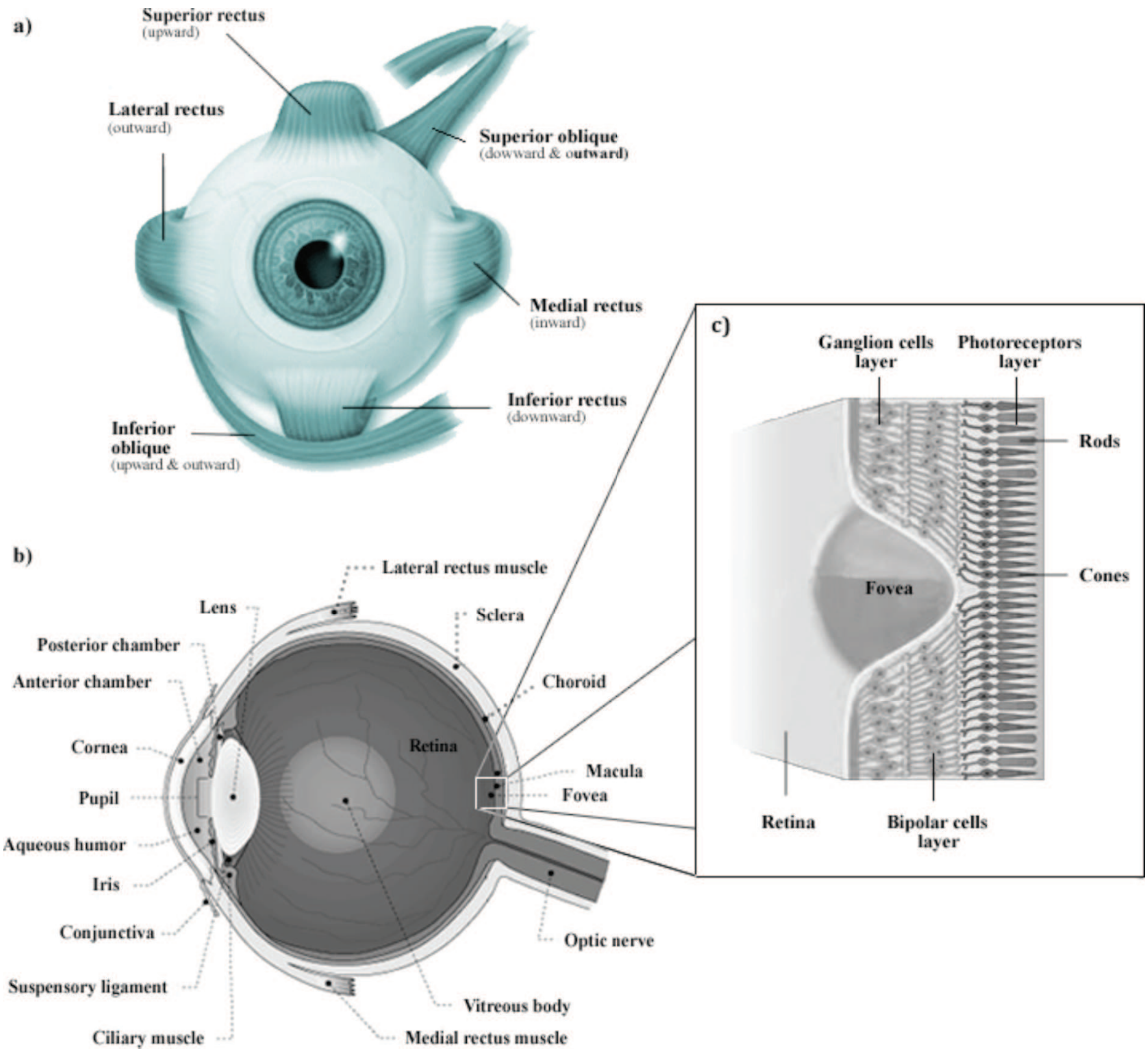

Figure 2.2. Panel a) shows the three pairs of eye muscles (and their action on the eye ball; adapted from Jayarathna, n.d.) and panel B) the anatomy of the eye and the location of the fovea on the retina (white frame; adapted from Harcourt Carter Optical, 2010). As depicted in Panel C, the fovea is the retinal part that contains quasi exclusively cones. Furthermore, because proximal neurons stray from the center of the retina, light has the most direct pathway to photoreceptors, making the fovea the most accurate part of the retina (adapted from Brain Connection, n.d.).

Rizzollatti, Riggio, Dascola & Ulmità (1987) proposed a more radical view in claiming in their premotor theory that attentional shifts are "planned-but-not-executed saccades" (Wright & Ward, 2008, p. 141). This model assumes consequently that attentional and ocular foci are controlled by a unique system. However this view is arduous to defend. If attentional shifts are unexecuted saccades, observers unable to move their eyes should not be capable to orient their attention as well. Patients' studies make this argument untenable. People suffering from progressive supranuclear palsy, a degenerative disease of the colliculus superior neurons, present in the early stage of the disease difficulties to disengage eyes from their current position but can shift their attention (Rafal, Posner, Friedman, Inhoff & Bernstein, 1988). Similar findings were observed in people suffering from congenital blindness (Garg et al., 2007). These observations suggest that attentional and ocular shifts do not stem from a common system but rather that they are interdependent. This assumption is supported by neuroimaging studies (Beauchamp, Petit, Ellmore, Ingeholm & Haxby, 2001; Corbetta et al., 1998) reporting some common neural activation sites during attentional and oculomotor orienting tasks.

Visual search studies provide additional evidence for a link between attention and eye movements. Precluding eye movements can degrade performance during a visual search task (Scialfa & Joffe, 1998), but not always (Klein & Farell, 1989; Maioli et al., 2001). Similarly to manual reaction time results, oculomotor parameters demonstrate differences between pop-out and conjunction search tasks (Williams, Reingold, Moscovitsch & Behrmann, 1997**;** Zelinsky & Sheinberg, 1997). More fixations were observed in conjunction than in pop-out tasks proportionally to the number of displayed items, reflecting consequently search efficiency. Conjugating the preview paradigm with the attentional capture (e.g., Theeuwes, 1991, see above), Ludwig and Gilchrist (2002) found more attentional capture by the abrupt onset of an irrelevant singleton when participants were asked to respond by foveating the target than by button-pressing. Moreover, distractors similar to the target provoked more attentional capture than other distractor types. They suggested that the disruptive effect of the irrelevant stimulus onset on the saccade programming can be modulated by the goal-driven properties of the distractor (its similarity to the target). According to Ludwig and Gilchrist (2002), saccade programming seems to be generated by an interaction between stimulus- or goal-driven strategies within a single oculomotor saliency map. As the overall saliency map guides attention to the most salient target (Wolfe, 1994), the oculomotor saliency map may direct eyes toward the most salient target (Shen, Reingold & Pomplun, 2000; for a similar idea see Findlay & Gilchrist, 2005; Findlay & Walker, 1999; Hamker, 2004).

The existence of such a map at the level of the oculomotor system is reinforced by a study I conducted investigating the effect of redundancy on oculomotor parameters. According to saliency-based models, as Guided Search (e.g., Wolfe, 1994), due to its larger contrast with its environment, a redundantly defined object generates a higher saliency peak than a singly defined target in the same context. If the speed at which attention is oriented to the target depends on the saliency peak strength, a redundantly defined target should be detected faster than a singly defined target. This hypothesis was confirmed repeatedly by behavioral data (e.g., Krummenacher et al., 2001, 2002 a, b; see Section 2.1.1.). If eye movements are effectively controlled by a similar dimension-based saliency signal, a saccade towards a redundantly defined target should be elicited faster than a saccade towards a singly defined target. This particular issue was investigated in Chapter 5 of this work.

According to previous sections, the different features from a sensory modality seem to be processed independently and in parallel, and integrated according to a parallel co-active processing model (especially vision). Furthermore, this model seems to be valid not only at a manual, but also at an ocular reaction times level. These findings demonstrate thus that attentional and oculomotor systems present similarities in their functioning. However, they do not necessarily implicate that both systems represent two facets of the same coin, but suggest that they are strongly interdependent. Finally, findings on the temporal feature integration suggest that some visual features require a longer processing latency than others, leading to an optimal integration when features are not presented simultaneously. However, studies presented so far focus on the processing of a single sensory modality, but, in daily life, a healthy human being does not exclusively rely on information from a unique sensory source. Instead, he processes and combines a multitude of information stemming from all sensory modalities to react appropriately to his environment. But, does the perceptual system integrate features from different sensory modalities as it seems to do for unimodal features? In other terms, is feature integration processing sensory-specific or supramodal?

2.6. Cross-modal integration

Imagine that you are in a movie theatre and waiting impatiently to watch the last James Bond. When the movie starts, you remark rapidly that there is something wrong. There is a slight shift between video- and soundtracks that ruins your pleasure. This example illustrates first that the human being integrates information from different sensory modalities without difficulty in daily life. Secondly, it points up our sensitivity to a dysfunction in multisensory integration. However, the following studies demonstrate that multimodal features are not always correctly integrated.

2.6.1. Multisensory illusions

A manifestation of a failure in the multisensory integration is the McGurk effect (McGurk & McDonald, 1976). When people talk, the sounds they generate correspond to the lip movements they produce. But what would the percept look like if both types of information do not coincide? McGurk and McDonald investigated this issue by displaying simultaneously one syllable through a microphone (e.g., “ba”) and the lip movements of another syllable on a screen (e.g., “ga”) and asked their participants to report what they perceived. Their results showed that 98% of their observers did report neither the auditory, nor the visual stimulus, but rather the compromise syllable “da”. This observation reflects that, although lip movements are not necessary to its understanding, they help to follow a conversation, especially in a noisy environment (Massaro, 1987).

A conflict in multisensory integration is also at the origin of a striking phenomenon called ventriloquism effect. All the talent of a ventriloquist resides in its ability to lend her/his voice to a dummy without moving her/his lips. This illusion works only if the dummy’s mouth movements are coordinated with the artist’s voice. Howard and Templeton (1966) explained this phenomenon by a capture of the auditory stimulus by the visual stimulus. According to Wright and Ward (2008), this unidirectional capture originates from the localization uncertainty associated to auditory stimuli. Indeed, a visual stimulus can be localized easier and with a higher accuracy than an auditory stimulus. In the case of the ventriloquism effect, due to the greater difficulty to localize the spatial source of the auditory stimuli, ventriloquist words can be imputed to the lip movements of the dummy. However, this illusion depends on the distance between auditory and visual sources. From a discrepancy of 30° of visual angle between stimuli sources, this effect disappears (Bertelson, 1999; Jack & Thurlow, 1973, in Wright & Ward, 2008).

Vision can “capture” audition, as observed in the ventriloquism effect, but also touch. In the rubber gloves illusion (Pavani, Spence & Driver, 2000), participants’ gloved hands were placed under a board. In each hand, participants held a squared sponge that delivered tactile (vibration) stimuli (one on the top and the other on the bottom of the sponge). Two wooden cubes were fixed to the board at the same position as the sponges and displayed visual stimuli through LEDs that were placed at the same position as vibrators on the sponges. In the first condition, participants were instructed to simply report the vertical position (up or down) of the tactile stimuli. In two other conditions, participants had to perform the same task, but two cotton wool filled rubber gloves were added on the top of the board, giving the impression of “holding” the wood cubes. In one condition, the alignment of the gloves and participant’s arms coincided, whereas in another one, they did not. After the behavioral task, participants fulfilled a questionnaire about their sensations during the experiment. Results indicated that reaction times were faster when visual and tactile stimuli were congruent (i.e., both stimuli on the same side), and even more when the gloves were aligned with participant’s arms. Furthermore the questionnaire responses demonstrated that participants reported more often the illusion that the gloves were their own arms when both were aligned.

Though the previous studies let suggest that visual modality dominates (“captures”) the other senses, vision can also be captured. Shams, Kamitani and Shimojo (2002) reported a “visual illusion induced by sound”. In this illusion, participants were asked to indicate the number of visual stimuli they perceive and ignore the auditory ones. Surprisingly, when a single visual flash was accompanied by several auditory beeps, participants reported to see several flashes. Similar results were observed with auditory-tactile (Bresciani, Ernst, Drewing, Bouyer, Maury & Kheddar, 2005) and visuo-tactile stimuli counting (Bresciani, Dammeier & Ernst, 2006). In both studies, the irrelevant stimuli disturbed the perception of the number of stimuli displayed in the other sensory modality. At the visuo-auditory level, Jousmäki and Hari (1998) could induce a so-called parchment skin illusion. Their participants wore rubber gloves and were instructed to rub their hands together. Simultaneously, microphones recorded the sound produced by their hand rubbing that was delivered via headphones as auditory feedback. When this sound of rubbing was accentuated by 15 Hz, participants reported the feeling that their hands became drier, like parchment paper.

2.6.2. Attentional shift across modalities

Studies investigating multisensory illusions provide thus evidence that our senses can mislead us in an experimental setting. Furthermore, due to their artificial character, they give support as well for an integration of sensory modalities under normal conditions. For instance, when a dog barked suddenly in someone's back, she or he would certainly turn back to see whether the animal represents a threat. Similarly, when a gazelle notices a suspicious sound from a bush, it will automatically gaze at the sound location. In such a case, an event generated in a particular sensory modality seems to be able to orient attention in another modality. Furthermore, to orient correctly visual attention to the location indicated by the sound, signals coming from both modalities have to be integrated to generate an adequate reaction to the environment.

2.6.2.1. Behavioral aspects

Attentional shift between sensory modalities can be investigated by designing variations of Posner's (1980) cueing paradigm including different sensory modalities. Although it is not clear whether each sensory modality can efficiently cue all others, visual and auditory cue validity influences performances in discriminating the position of a visual flashed stimulus (Ward, 1994). Spence and Drives (1997) found that only auditory cues had a cross-modal effect. In this study participants had to indicate the vertical position of the target stimulus. The target stimuli were presented on one side (left or right), either on a lower or upper position, while cues were displayed either to the left or the right at the same horizontal position than the fixation point. Participants had to indicate the vertical position of the target stimulus, whereas the cue pointed the probable side of the target onset. Results showed that only auditory cues influenced the vertical position discrimination of the visual target. However, McDonald and Ward (2000) observed a validity effect of a briefly presented (100-300ms) auditory cue on a visual target side discrimination task, namely a reaction time enhancement for trials displaying invalid cues. A reciprocal cross-modal modulation is also observed in discriminating the position of a visual stimulus cued by a tactile stimulus and vice versa (Butter, Butchel & Santucci, 1989). McDonald, Teder-Sälerjärvi and Hillyard (2000) designed an experiment in which an irrelevant auditory cue was displayed either at the left or the right of the fixation point, followed by a brief visual mask either at the same or at the opposite location as the cue. In half of the trials, a faint visual target was briefly presented before and at the same side of the mask. Participants' task was to react only at the target presence. Though task-irrelevant, the auditory cue biased target detection according to its validity.

2.6.2.2. Neurophysiological aspects

Though a bidirectional cross-modal cueing effect is not systematically observed, results of previous studies give support for an inter-sensory spatial coordination. Further evidence in favor of this account is found in electrophysiological studies (e.g., for review see Eimer & Driver, 2001). Indeed, in contrary to Spence and Driver's (1997) behavioral results, McDonald and collaborators (McDonald, Teder-Sälerjärvi, Heraldez & Hillyard, 2001; McDonald, Teder-Sälerjärvi, Di Russo & Hillyard, 2003; McDonald & Ward, 2000) observed a modulation of event related potentials (ERPs) for visual targets induced by auditory cues.

In a series of studies, Eimer and his collaborators investigated whether an endogenous spatial cue can modulate ERPs pattern of different sensory-defined targets. Eimer and Schröger (1998) designed an experiment in which a visual central cue indicated the probable location of the target (50% validity) which could be either a sound or a flash. Participants had to respond only when the target coincided with the location indicated by the cue. In one half of the experiment, only visual targets were task-relevant (auditory targets had to be ignored), whereas in the other half, auditory stimuli were relevant. Results showed that, although being target modality-specific, ERPs patterns for both types of targets were significantly modulated by the validity of the visual cue. Moreover, even the ERPs for to-be-unattended targets were similarly affected by the cue validity. These observations demonstrate thus that brain activity is modulated by cross-modal attention. In a study based on the same paradigm and using visual combined with tactile targets, Eimer and Driver (2000) noticed cross-modal modulation only in visual ERPs. In another study (Eimer, van Velsen & Driver, 2002) the target stimulus could be either auditory, or tactile, or visual. In one half of the experiment, tactile stimuli were task-relevant, while in the other half participants had to react only to auditory targets. As in previous experiments, results revealed a modulation of the ERPs patterns for visual and auditory targets when the tactile stimuli were task-relevant, but only for visual targets when auditory stimuli were relevant. Furthermore, not only visual cues, but also auditory cues can generate ERP modulations for the task-irrelevant targets (Eimer & van Velsen, 2002). Using a slightly different paradigm, Eimer, Cockburn, Smedley and Driver (2001) observed that ERPs for irrelevant auditory and visual targets can be affected by somatosensory spatial attention.

Finally, a modulation of ERPs for irrelevant stimuli could be observed not only between, but also within hemifields (Eimer & van Velsen, 2005; Eimer, van Velsen & Driver, 2004).

ERP studies demonstrated that a cross-modal shift of attention modulates brain activity, providing consequently additional evidence for a supramodal control of attention. Nevertheless, this method does not permit a precise localization of the source of this activity modulation. A response to this question can be found in neuroimaging studies. In a functional magnetic resonance imaging (fMRI) study, participants were instructed to indicate the vertical position of a visual or a tactile target that was preceded by a symbolic highly valid auditory cue (Macaluso, Frith & Driver 2002). Comparing invalid to valid trials revealed an enhanced activation of regions of the inferior frontal cortex and the temporo-parietal conjunction, independently of the target modality. These regions are similarly activated in a visual spatial cueing task (e.g., Corbetta & Shulman, 2002 for review). Furthermore, irrespective of the cue validity, the superior premotor cortex and the intraparietal sulcus were activated, regions also thought to be involved in the orienting of visual attention (Corbetta et al., 1993; Gitelman et al., 1999; Nobre et al., 1997). Finally, in a similar experiment, Macaluso, Eimer, Frith and Driver (2003) demonstrated that a cross-modal endogenous attention shift modulates the intraparietal sulcus and the middle occipital gyrus activity even before target onset.

Investigating this issue with another approach, Shomstein and Yantis (2004) observed a transient activity of the superior parietal lobule during an attentional shift between sensory modalities, regardless of the shift direction. In this study, visual and auditory alphanumeric stimuli were presented serially and at a rapid rhythm (rapid serial presentation paradigm). At each frame, five visual stimuli formed a cross, while two auditory stimuli were presented monaurally to the left and right ears and the central stimulus was displayed binaurally. At the beginning of the experiment, participants where instructed to pay attention to one of the streams. When a target appeared (either the number 2 or 4), they had to either maintain their attention on the same stream, or to shift to the other stream according to the target type. When attention was shifted from the auditory to the visual stream, activity in the auditory cortex diminished and increased in visual cortex. The reversed pattern was observed in the opposite shifting direction. Nevertheless, during the modality shift, the superior parietal lobule was transiently activated, demonstrating the importance of this structure in attentional cross-modal shift.

Similarly, Downar, Crawley, Mikulis & Davis (2000) employed a trimodal serial presentation in which participants were passively exposed to visual, auditory and tactile stimuli. At each frame (14s), a stimulus in a single modality differed from the previous frame. Experimenters observed activation in the temporoparietal junction, inferior frontal gyrus, insula and left cingulate and supplementary motor areas during this passive modality transition - brain regions also involved in visual attention shift (e.g., Corbetta & Shulman, 2002).

Behavioral and electrophysiological studies revealed thus that, like in a unimodal paradigm (e.g., Posner et al., 1978, 1980 in vision), the three most investigated senses - visual, auditory and tactile modalities - can produce a goal-directed attention shift in each other modality. Furthermore, neuroimaging findings revealed that many brain structures involved in a cross-modal shift of attention are also activated during visual attention orienting. The fact that uni- and cross-modal paradigms examining attention shifts present comparable behavioral results and seem to involve the same brain network suggests therefore that orienting of attention observed in each modality stems from the same supramodal control of attention. Furthermore, it leads to the reasonable assumption that, as in multisensory illusions, sensory modalities have to be integrated to generate a coherent representation of the environment. A change in one of these modalities will affect this representation and guides attention in other modalities toward the change location.

2.6.3. When sound enhances vision

A change or a cue displayed in a modality can not only capture attention in another modality, but also improve performance in a task designed in another modality. This seems to be especially true for auditory stimuli in visual tasks. In a set of experiments, Vroomer and de Gelder (2000) showed participants a series of trials consisting of four briefly presented frames. Each frame, composed of a pattern of four dots, was accompanied by a tone and followed by a mask. In one of these frames, a target pattern was displayed (dots forming a diamond shape), and participants' task was to indicate the spatial location of this specific pattern. The sequence of frames was repeated until the participant answered. Vroomer and de Gelder observed that the probability of identifying the correct target position increased when the tone displayed with the target was different than the one accompanying the other frames.

Furthermore, participants reported an illusion of "freezing", in which the target frame seemed to last longer than distractor frames.

A similar facilitation of task-irrelevant auditory stimuli was observed in a sequential visuo-auditory search task (Dalton & Spence, 2007). At each trial four sequences were presented associating a visual stimulus (a white square) with a tone. In different blocks, participants were asked to attend either to visual or auditory stimuli and to generate a speeded response concerning the duration of a target stimulus, which was either shorter or longer as the three others. In some trials, the duration of a stimulus in the task-irrelevant modality also differed and could be presented within the same sequence as the target or not. Results revealed that only an irrelevant auditory stimulus can improve task performances for a visual target when they are both displayed in the same sequence. Similarly, the detection of a flashed light followed by a mask can also be enhanced when a sound is simultaneously presented with the visual target (Frassinetti, Bolognini & Làdavas, 2002). Finally, a synchronous task-irrelevant sound can facilitate the detection of a visual target in a hard visual search (Van der Burg, Olivers, Bronkhorst & Theeuwes, 2008). In this study participants had to indicate whether a vertical or horizontal bar was present in an array of tilted bars. Each element altered its color (from green to red) many times per trial and at its own speed. The target kept its color for 900ms on average and, when it changed, it was the only element in the display which did so. Finally, beeps accompanied half of the trials. Results showed a reaction time decrease in the condition with the sound and. additionally faster search times when beeps occurred synchronously with target color changes.

2.6.4. Cross-modal redundancy effects

The fact that an additional irrelevant auditory stimulus can enhance performances in visual tasks can only be possible if the different modalities are integrated, as already observed in multisensory illusions and cross-modal attention shift. One further line of arguments rises from studies involving multisensory redundant stimuli. As already observed with visual stimuli (see above), two stimuli from different modalities are faster detected than a single stimulus from one of both modalities. Although most of the multimodal redundancy gains are observed in visuo-auditory paradigms (Arndt & Colonius, 2003; Colonius & Arndt, 2001; Gondan, Niederhaus, Rösler & Röder, 2005; Hughes, Reuter-Lorenz, Nozawa, & Fendrich, 1994; Miller, 1982, 1986; Molholm, Ritter, Javitt & Foxe, 2004; Molholm et al., 2006; Patching & Quinlan, 2004; Raab, 1962), visuo-tactile (Forster et al., 2002), auditory-tactile paradigms (Diederich & Colonius, 2004), and trimodal paradigms (Diederich & Colonius, 2004) showed also a faster detection of redundantly defined stimuli. Finally, by using or adapting Miller (1982, 1986)'s race model inequality (see above), most of these studies were able to demonstrate that multisensory stimuli are processed in a parallel co-active way. Because a parallel co-active processing model postulates a neural summation of signals activation, this observation gives additional support for cross-modal feature integration.

Although previous behavioral studies provide some evidence for a neural summation of multisensory signals, they are not able to point out its location at the brain level, or the structures involved in its network, respectively. However, some neural structures are good candidates and one of them is the colliculus superior (for review see Stein & Stanford, 2008). Single cell recording studies demonstrated that the activity of colliculus superior cells is deeply affected by multisensory stimuli, reflected either by a firing rate increase or decrease (Meredith & Stein, 1986). Furthermore, multisensory stimuli reduce the physiological response latencies of these cells and enhance their initial response phase (Rowland, Quessy, Stanford & Stein, 2007). In addition, lesions of this structure generate multisensory behavioral deficits in orienting of multisensory attention (Burnett, Stein, Perrault & Wallace, 2007). FMRI studies in human observers demonstrated an activation change at the level of the colliculus superior when multisensory stimuli were presented (Clavert, Hansen, Iversen & Bramme, 2000; Dhamala, Assisi, Jirsa, Steinberg & Kelso, 2007).

The superior parietal lobe seems also involved in the neural summation. In monkeys, 70% of the cells of the ventral intraparietal area modified their response when visuo-tactile stimuli were presented (Avillac, Hamed & Duhamel, 2007). Human intracranial recordings provide similar results in superior parietal lobe (Molholm et al., 2006). An activity modulation in this structure was also observed in an fMRI study displaying visuo-auditory stimuli (Calvert et al., 2000). Two others areas showed activity modulation during visuo-auditory stimuli integration, namely the superior temporal sulcus and its surrounding gyri (Beauchamp, Lee, Argall & Martin, 2004; Calvert et al., 2000) and the prefrontal cortex region (Beauchamp et al., 2004; Calvert et al., 2000; Dhamala et al., 2007). The fact that the activation of these brain regions is modulated by multisensory paradigms (attentional shift and redundant stimuli) makes them thus a highly probable location of the multisensory integration.

2.6.5. Temporality and cross-modal integration

The last section provides clear support, especially through violations of the race model inequality, in favor of multisensory feature integration. Nevertheless, this observation indicates only that a neural summation of multisensory features occurs but provides no information about its time cours (see *Chapter 3.3.1.*).

Similar findings were observed at a multisensory level. In tasks investigating participants' judgment about the temporal order of multisensory stimuli onset, the subjective perception of a simultaneous stimuli onset appears very seldom when stimuli onset is objectively synchronous. A point of subjective simultaneity (PSS) is reached when a visual stimulus is displayed between 20 and 80ms before an auditory stimulus (51ms in Stone et al. 2001; between 19 and 34ms in Zampini, Guest, Shore & Spence, 2005; between 60 and 80ms in Zampini, Shore & Spence, 2003) and 10ms before a tactile stimulus (Spence, Baddeley, Zampini, James & Shore, 2003).

Although participants of one study (Slutsky & Recanzone, 2001) presented a PSS around 0ms, the 20 to 80ms inter-stimuli interval required to perceive two visuo-auditory stimuli as synchronous is consistent with neurophysiological data demonstrating that auditory signals reach the superior parietal lobe 30ms before visual inputs when displayed simultaneously (Molholm et al., 2006). Altogether, behavioral and neurophysiological observations demonstrating that an optimal multimodal integration occurs when stimuli are presented asynchronously suggest that features form different sensory modalities are not processed at the same speed.

This hypothesis is reinforced by studies investigating the temporal integration of multisensory features in an onset detection task. Diederich and Colonius (2004) designed an experiment in which participants were asked to react at any stimulus onset (either a flash, or a tone, or a vibration). Stimuli could be presented either alone (unimodal), or in pairs (bimodal), or altogether (trimodal). In bi- and trimodal conditions, the stimuli onset could be separated by a variable stimulus onset asynchrony (SOA). They observed that sensory modalities were integrated at best for bi- and trimodal stimuli when the SOA between stimuli onset was equivalent to the reaction time difference between the uni- and bimodal stimuli respectively. Furthermore, in all tested combinations, the optimal integration never occurred at synchronous stimuli onset.

Although providing evidence that multisensory integration depends on the relative speed of feature processing, most of the previous cited studies used only one or two stimuli at each trial, what is far away from the number of stimuli a human being is daily confronted to. In addition, due to this reduced number of items, participants do not need to select the relevant object. However, as reported above, selection is a crucial part in feature processing. To take account of this factor, I designed a study investigating temporal integration of visuo-auditory stimuli under search conditions. Inspired from the feature change detection paradigm (Schönwälder, 2006; see Section 3.3.1.), participants faced an array of visual stimuli accompanied by a tone and were instructed to react at any stimulus change. In single change trials, either all visual elements changed (unveiling an odd target), or the tone frequency decreased or increased. In redundant change trials, visual and auditory changes were separated by a variable SOA. Results of this study are discussed in details in chapter 4.

2.7. Discussion

The last sections provided behavioral and neurophysiological evidence that assuming an independent parallel processing of each sensory modality is hardly tenable. If features from different sensory modalities were not integrated at some point in their processing, no multisensory illusion should occur. Furthermore, if only information from the modality in which attention is actually engaged in could be processed, no cueing effect should be observed in behavioral and electrophysiological multisensory paradigms, as an irrelevant auditory stimulus should not be able to facilitate the resolution of complex visual tasks. Finally, neither redundancy gains, nor race model inequality violations should be reported.

Additionally, although not having systematically their own equivalent in each modality, the four clues of an feature integration that were presented in this work, namely sensory illusions, cueing, attentional shift paradigms, and violations of the race model inequality (Miller, 1982, 1986), can be observed for features within each discussed sensory modality. The fact that similar results for these clues can be found within and between sensory modalities give strong support for a supramodal feature processing system governed by mechanisms that take account of both temporal and spatial feature properties. According to research in vision (e.g., Wolfe, 1994) and audition (Kayser et al., 2004), one likely plausible mechanism for the spatial selection is the saliency map that integrates saliency signals from the different object dimensions to guide attention toward the most salient object.

This supramodal system is supported by neuroimaging studies (e.g., Calvert et al., 2000) demonstrating that paradigms involving multisensory features recruit brain areas that are also activated during unimodal paradigms (at least in vision; see Calvert & Thesen, 2004 for a review of the multimodal areas).

Finally, a supramodal processing system can provide an answer to the debate between the early or late stage of feature integration. According to the supramodal processing system, if each indicator has the same meaning in uni- as in multimodal paradigms, the fact that recent research could demonstrate that visual feature integration occurs at an early stage (Töllner et al., in press) give consequently indirect evidence that feature integration should occur at an early stage in each modality or modality combination. Although this question does not seem to be tackled at neither auditory, nor tactile level, recent studies support this position for the integration of multisensory features. For instance, a lesion of multimodal areas does not alter performances of monkeys in tasks involving crossmodal matching and transfer (Ettlinger, 1990). Furthermore, multimodal stimuli can modulate activation in brain areas traditionally considered as unimodal (Falchier, Clavagnier, Barone & Kennedy, 2002; Foxe, Morocz, Murray, Higgins, Javitt & Schroeder, 2000; see for a review Kayser & Logothetis, 2007).

In summary, actual research cumulates massive evidence in favor of a parallel co-active feature processing ruled by a supramodal system taking account of both spatial and temporal properties of features. Furthermore, feature integration seems to occur at an early stage in processing. Even tough plausible, further research is needed to confirm the existence of a supramodal feature processing system. Additional investigations are required to validate the hypothesis of a feature integration occurring at an early level. First, this hypothesis has to be empirically confirmed in audition and in touch. Second, in agreement with Kayser and Logothetis (2007), the fact that activation in unisensory brain regions can be modulated by signals from other sensory modalities does not necessary mean that multimodal featural signals are already integrated in unisensory areas.

As outlined in the course of this theoretical background, the present work was aimed at a better understanding of feature processing and integration. The two next chapters focus on the temporal properties of the feature signals integration under search circumstances within a sensory modality - as vision (Chapter 3) - and between sensory modalities (Chapter 4), whereas the spatial aspect of feature integration in visual search tasks is investigated in Chapter 5. The purpose of Chapter 6 was to test the effect of practice in visual feature signals integration. Finally, Chapter 7 investigates the ability of participants to learn through repetitions the association between spatial and featural aspects of the search display (termed "contextual cueing") and the impact of a featural change on this phenomenon.

3. Relative processing time of feature signals in visual search depends on task requirements

3.1. Abstract

Visual information processing is massively parallel and carried out on pathways with different temporal properties. However, visual features need to be integrated to create coherent object percepts. Integration may be based on spatial and/or temporal mechanisms. While cognitive models of selective visual processing (e.g., Wolfe, 1994) focus on spatial mechanisms of feature integration, the temporal aspects have been somewhat neglected. To examine the characteristics of temporal integration of visual signals, participants of the present study were presented with visual search displays in which the identity of the target was initially masked and only revealed after two feature changes that were separated by variable time intervals. Three different pairs of visual features (color, orientation and motion) were investigated under two different task requirements. In a first set of experiments, participants had to respond to any change in the display (detection task), whereas, in the second series of experiments, they were instructed to respond only to predefined feature combinations (conjunction task). The introduction of a time interval between feature changes in the detection task revealed that orientation or motion changes precede color by 20 ms to generate the fastest detection reaction times, whereas simultaneous changes of color and orientation signals generated the fastest reaction times. These results demonstrate that processing times of visual features are variable. The results of conjunction search tasks showed a reversed reaction time pattern, in which target identification time decreased according to the time interval between signal changes. Further, although the longest reaction times were observed when features changed synchronously, further analyses suggest a difference in feature processing times in conjunction tasks, too.

3.2. Introduction

Visual search is part of our everyday life; this minute, I was looking for my mobile phone, my keys, and a red pen. In general, these objects are rapidly found because they present mostly different features as the neighboring objects. In this case, they are so conspicuous that they literally "pop out" of the visual scene. A red pen is easy detectable in a box containing blue pens, whereas the Pisa Tower stands out from the surrounding buildings principally because of its (dangerously unusual) orientation, and a camouflaged animal becomes visible when it moves. An object presenting an odd feature, as color, orientation, or motion, is thus fast detected among homogeneous surrounding elements (e.g., Treisman, 1988).

The pop-out phenomenon can be explained by the widely accepted mechanism of contrast summation, also referred to as saliency models (e.g., Cave & Wolfe, 1990; Koch & Ullmann, 1985; Wolfe, 1994). According to these models, features of the visual scene are analyzed in parallel (a concept supported by neurobiological data, see Tessier-Lavigne, 2000, for a review), and each of the features is represented on independent spatially organized maps that computes the local contrasts (or saliency) between different values of features. Contrast signals generated on feature-specific maps are then summed up onto an overall (master) saliency map that guides attention to the location with the largest contrast. In other terms, the more an object contrasts to its neighbors, the higher the probability that it will attract attention.

Contrast summation models thus provide a plausible explanation about the way the visual system can detect the presence of an object that differs from homogeneous distractor objects by one salient features. However, do the same mechanisms underlie detection if an object differs from distractors by more than one feature? It is well established that, when participants have to detect the onset of physically separate stimuli, manual reaction times are faster when two targets are displayed compared to only one target (e.g., Miller, 1982, Mordkoff, Yantis & Egeth, 1990; Raab, 1962; Turatto, Mazza, Savazzi & Marzi, 2004). Similarly, expedited reaction times are observed in visual search tasks; a dimensionally over-defined (redundant) odd-one out stimulus (e.g., a red horizontal bar among green vertical bars) is detected faster than a dimensionally singly defined stimulus (e.g. red vertical bar among green vertical bars, see Koene & Li, 2007; Krummenacher, Müller & Heller, 2001, 2002a, b; Poom, 2009). Speeded reaction to redundantly defined targets is termed the redundant signals effect (RSE) or redundancy gain (RG).

An explanation for the redundancy gain phenomenon is found either in statistical facilitation (e.g., Raab, 1962) or parallel co-active processing (e.g., Miller, 1982). Raab's parallel race model postulates a competition between features in which the first fully processed feature (i.e., the winner of the parallel race) triggers the response. Assuming that there is a certain overlap between the reaction time distributions to different features, each feature is expected to win the race a proportion of trials. Reaction times to redundantly defined objects are therefore, on average, faster than reaction times to singly defined targets. Miller (1982) suggests that, similarly to contrast summation, the response depends on the summation of the processing activation (accumulation of activation) of the two relevant features. When activation accumulation exceeds a certain threshold, the response is triggered. Miller showed that all models postulating strictly parallel processing (models in which features are processed independently and simultaneously) must not violate the following inequality: $F_R(t) \leq F_{T1}(t)+ F_{T2}(t)$, where t is the time since display onset and F the cumulative function of the reaction times. T1 and T2 correspond to the features defining the redundantly defined object R. Violations of Miller's inequality (called the "Race Model Inequality", RMI) provides evidence against parallel processing and in favor of parallel co-active processing.

With help of Miller's (1982) RMI, it was shown that visual features are processed in parallel co-active fashion (Krummenacher, et al., 2001, 2002a, b; see also Koene & Li, 2007; Poom, 2009). This observation therefore provides additional support for contrasts summation models. A redundantly defined object generates a large saliency peak on the overall saliency map due to several peaks at the same spatial location on feature-specific maps, whereas a singly defined object only generates a unique peak on a single feature map. According to the contrast signal summation principle, a redundantly defined object generates a larger contrast peak at a single location in the master map than a singly defined object, thus focal attention, in redundant target trials, is directed faster the most salient object than in non-redundant target trials (Krummenacher et al., 2001).

However, not all visual feature combinations seem to be processed in a parallel coactive way. In a pop-out search task involving either singly or redundantly defined Gabor patches (defined by color, orientation, motion and spatial frequency), Poom (2009) observed violations of Miller's (1982) RMI for all features combinations, except for color-orientation and motion-color combinations. Similarly, in a study by Koene and Li (2007), participants had to indicate in which side of a pop-out search display (left, right) an odd target object appeared. This target could be either defined by one or two features (on the color, orientation and motion dimensions). Although all redundant feature combinations generated faster reaction times than single features, the motion-color combination did not generate violations of the RMI.

These results seem to contradict the contrast summation hypothesis, because the hypothesis postulates contrast summation for all (types of) visual features. If all feature contrasts were processed at the same speed and were summed onto the master map, a motion-color defined object should generate RMI violations just as any other combination of features. Li (2002) proposed an alternative model (based on the behavior of cells in V1 and thus termed the “V1 hypothesis”) that gives a plausible explanation for this lack of RMI violations of objects defined by motion and color. Li assumes that activation generated by cells in the primary visual cortex (V1) whose receptive fields are tuned to a particular feature or feature combinations underlies redundancy gains. Neuro-anatomical studies (e.g., Livingstone & Hubel, 1984) showed that, contrarily to cells coding motion-orientation and color-orientation combinations, there are only very few cells tuned to motion-color combinations in V1. According to Li’s model, each cell signals the information present in its receptive field, and the most salient location corresponds to the receptive field of the cell with the largest firing rate (no summation of feature-based information is therefore required). In the case of a red horizontal bar among green vertical bars, the cells tuned to color, orientation and cells tuned to color-plus-orientation fire, and because all types of cell fire, the response is triggered earlier in redundant target trials than in non-redundant target trails where only a subset of cells fires. However, in the case of an object defined by motion-plus-color, because of the lack of motion-color sensitive cells in V1, only the motion- and color-tuned cells fire in response to the stimulus, thus the firing rate cannot be stronger that the firing rate for motion or color. The distribution of cells in primary visual cortex therefore prevents RMI violations for targets defined by motion and color.

One alternative approach that could contribute to the explanation of signal integration in the perceptual system is the (often underestimated) fourth dimension: time. While many models of visual (feature) processing, such as the contrast summation model and the V1 hypothesis, focus on spatial mechanisms of feature integration, temporal aspects have been strangely neglected.

A (relatively small) number of studies investigating temporal characteristics of feature integration suggest that processing of different visual features is variable in time. Moutoussis and Zeki’s (1997a) participants were presented with a display in which green and red squares moved vertically up and down in a continuous (sinusoidal) fashion. Participants were asked to indicate which color was associated to which motion direction (attribute pairing task). The critical point was that the (motion direction and color) change frequency within a feature was identical for both color and motion, but the change cycles could be objectively synchronized or shifted relative to each other. As an example, in the case of an objectively simultaneous change, the squares were green when moving upwards and red when moving downwards, whereas, in an asynchronous condition, the color could change before or after the motion direction. Moutoussis and Zeki (1997a) observed that participants reported a synchronous color-motion change when motion changed 70 to 80ms before color. In a following series of experiments using the same paradigm Moutoussis and Zeki (1997b), investigated the temporal integration of orientation in function of color and motion. They observed that color was processed faster than orientation, and orientation was processed faster than motion. This processing bias toward color was replicated by several research groups (Adams & Mamassian, 2004; Arnold, Clifford & Wenderoth, 2001; Arnold & Clifford, 2002; Aymoz & Viviani, 2004; Bartels & Zeki, 2006; Bedell, Chung, Ogmen & Patel, 2003; Viviani & Aymoz, 2001).

According to these studies, not all visual features are processed at the same speed. This processing time difference suggests that visual features would be integrated (i.e., perceived together) in an optimal fashion when the slowest feature is allowed to start processing before the fastest one. Miller's (1982) RMI would therefore be violated most markedly, in a contrast summation model that would take into account such processing speed difference between features. In the common implementation of contrast summation models, both features of a given target start processing at the same point in time. If it is assumed that the generation of contrast signals in feature-specific maps is continuously reported (as it is being generated) to the master map as a function of the time, two features with the same processing speed will generate the amount of activation required to reach the detection threshold faster than two features with asynchronous processing speed. In the case of the same feature processing times, the relative contribution of both features to the processing activation accumulation is more or less equivalent. However, in the case of unequal processing times, the largest part of the summed activation comes from the faster of the two features. Although the overall saliency activation of redundant signals (with different processing times) reaches the detection threshold on average faster than in the case of a singly defined target the benefit might not large enough to generate RMI violations. Nevertheless, favoring the slowest processed feature by displaying it before the fastest feature should counterbalance the processing speed difference and allow faster activation accumulation; consequently, the detection threshold would be exceed earlier in time and hence detection RTs would decrease.

Schönwälder (2006) tested the temporal integration of motion and color in visual search tasks. Participants searched for targets defined by motion direction, color (singly defined targets), or by a combination of both motion and color (redundantly defined targets). Search objects moved across the display, and, in target-present trials, one or two features of one display object changed. In trials with a redundantly defined target object, the feature changes were separated by variable temporal asynchronies. Contrary to a motion-color processing asynchrony hypothesis assuming an optimal integration when motion precedes color onset (or change), RTs to motion-color targets were fastest when both features changed synchronously. However, this finding is coherent with Ulrich and Miller's (1997) mathematical demonstration that showed that features (or stimuli) should be optimally integrated when they change simultaneously. Furthermore, Ulrich et al.'s model predicts that the reaction times increase proportionally to the time interval between signal changes, a prediction confirmed empirically by Schönwälder (2006).

The present study was designed to contribute to a better understanding of the temporal integration of visual features under two visual search conditions. Color, orientation and local motion (i.e., sinusoidal object motion on a limited-extent trajectory) served as target-defining features. (The use of the type of motion with a limited trajectory allows observing whether different types of motion are integrated in a similarly.) It has been shown the motion characteristics influence perception of motion and color signals. For example, detection time for a color change in continually moving objects depends on the velocity of the moving objects (Kreegipuu, Murd & Allik, 2006); the faster the objects move the faster the color change is detected. Further, a static target is detected more easily among stimuli with defined by the same motion direction than stimuli moving on random paths (Royden, Wolfe & Klempen, 2001).

In the first set of experiments of the present study, the temporal integration of featural signals was investigated with a change detection paradigm (Experiments 1a to 1d). As in the study by Schönwälder (2006), participants were instructed to respond to any feature change occurring in the display. In trials involving redundantly defined targets, feature change onsets were separated by a variable asynchrony. In order to determine the optimal point in time of integration between each feature combinations, three different indicators were used, namely redundancy gains in the sense of Biederman and Checkosky (1970) and Miller and Lopes

(1988), the response enhancement index used to assess the strength of multisensory integration at a neuronal level (e.g., Meredith & Stein, 1986), and the extended version of Miller's (1982) race model inequality (RMI) taking into account onset asynchronies between stimuli (Miller, 1986).

3.3. Experiment 1a: Motion-color detection task

3.3.1. Method

Participants. Ten observers (7 female and 3 male) took part in Experiment 1a. All were students at the University of Fribourg. They were paid CHF 10. Their age ranged between 24 and 38 years (median = 27 years). All observers had normal or corrected to normal vision, including normal color vision.

Design. Each trial started with the presentation a blank screen for 500 ms, followed by the presentation of the search display. Three different sequences of events could follow (see Figure 3.1): (a) a change occurred in one of the features, (b) a change occurred in the two features, separated in time by variable SOAs, (c) or there was no change at all during the whole trial. If there was (were) change(s), the (first) change occurred after a variable delay of 800 to 1200 ms (five steps separated by 100ms). The display was presented for a maximum of 1500ms in change (go) trials, and 2000 ms in trials without a change (no-go trials). When the 2000 ms had elapsed, the next trial began with a blank screen.

*Stimuli and timing***.** Visual stimuli were 49 green vertical bars, each subtending 0.38° x 1.15° of visual angle that were presented on a grey background (RGB: 89, 89, 89). Because of the subjectively important difference between hues (e.g., Folk, Remington & Johnston, 1992), color isoluminance was not aimed at (RGB code for green: 0, 255, 0). Bars were displayed in the cells of a virtual 7x7 (rows x columns) matrix, subtending 13.56° x 14.25° of visual angle. The position of each item relative to the center of its matrix cell was randomly jittered in each trial (at a maximum distance of ±0.19° along the horizontal and vertical axes, respectively) to prevent collinearities with the other stimuli. During the trial all the elements moved horizontally (with a maximal amplitude of 1.15° of visual angle) to the left or the right with a speed determined by a sinusoidal function (α was set to 0 degree in the first frame and increased by 7 degrees per frame). In no-go trials, none of the stimuli of the moving display changed, and the participants were instructed to refrain from responding and to wait for the next trial to begin. In go trials, either the color of one bar changed (color condition), or the motion direction (motion condition), or both the color and motion direction changed (redundant condition). In the color condition, the color of one bar changed from green to red (RGB code: 255, 0, 0) or blue (RGB code: 0, 0, 255); in the motion condition, the bar moved along a virtual line diagonally tilted 62.25° to the left or right relative to vertical.

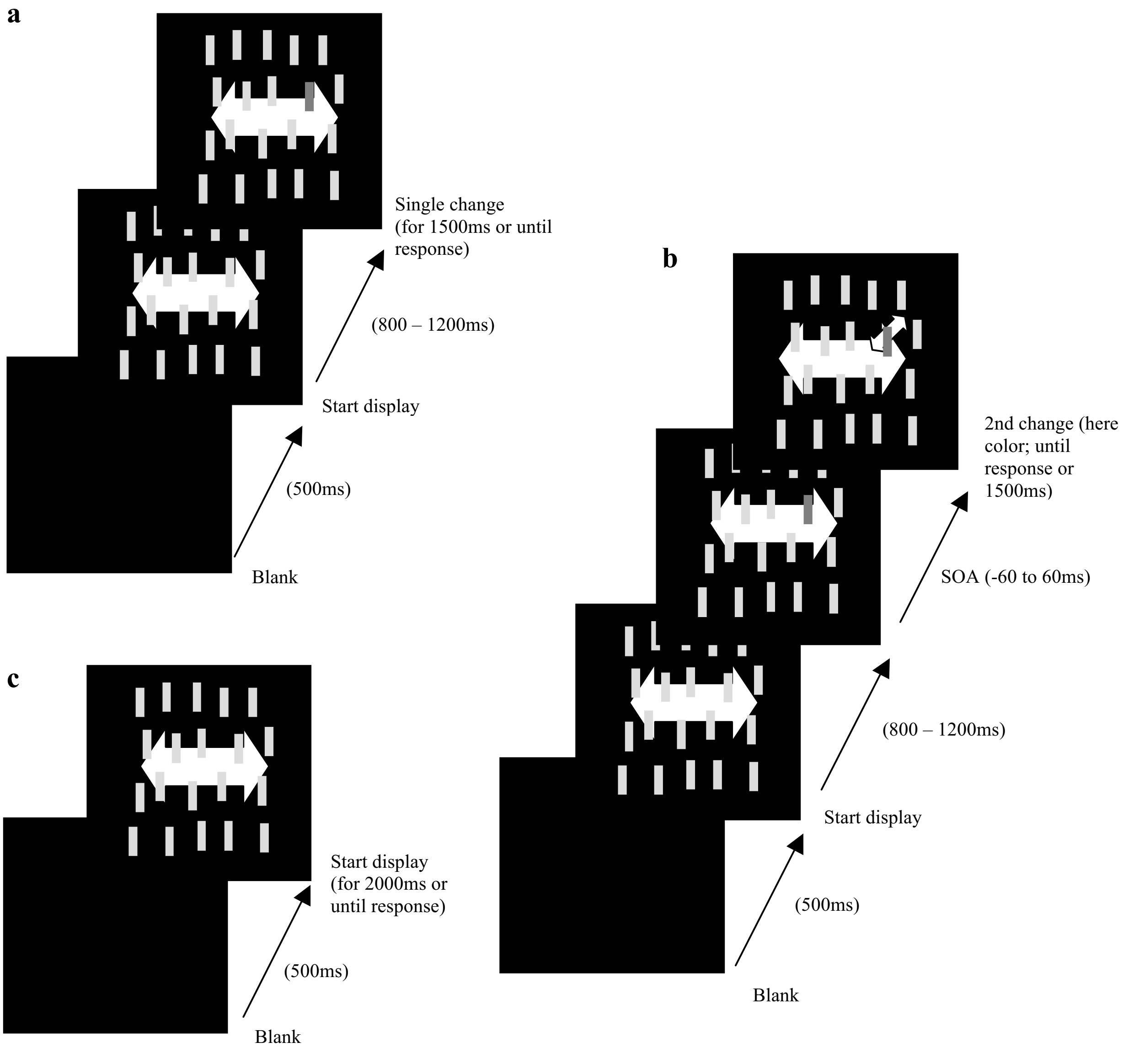

Figure 3.1. Design of Experiment 1a. The light grey stands for green, and the dark grey for red. The local motion of the whole display is symbolized by the large double-head arrow, whereas a target motion is indicated by a smaller tilted double-head arrow. **Panel a** represents a single feature change trial (either color or motion). **Panel b** stands for a redundant feature change trial in which feature changes are separated a certain time interval (SOA). **Panel c** represents a no change trial (in which no react was required).

In the redundant condition the feature change onsets could be asynchronous, namely the time between the changes of the two feature varied from -60ms to +60ms in seven steps of 20 ms including a condition where the two features changed synchronously (SOA = 0 ms) (see Figure 3.1 for an illustration). The minus (-) sign before the onset time asynchrony (in ms) signifies that the motion feature changed first and the plus (+) sign that the color feature changed first. The SOA values were chosen taking into account the refresh rate of the monitor (100 Hz). The reaction time was recorded from the onset of the change (from the onset of the first change in redundant change trials). To avoid edge effects, targets were presented in the inner 5x5 cells of the virtual grid.

*Apparatus and setting***.** Participants were seated at a distance of approximately 50 cm from a Philips Brilliance P202 19” monitor controlled by a HP Compaq Business Ultra Slim Desktop Dc7600 personal computer (Pentium IV at 3.2 GHz, 512 Mb RAM). The monitor resolution was set to 1280x1024 pixels and its refresh rate to 100 Hz. Experiment 1a was programmed using MatLab and the Cogent 2000 toolbox developed by the Cogent 2000 team at the FIL and the ICN and Cogent Figures developed by John Romaya at the LON at the Wellcome Department of Imaging Neuroscience. The experiment was conducted in a darkened room.

Procedure. Participants completed 1 “warm-up” block of 24 trials to become familiar with the task and 7 experimental blocks of 114 trials each. The whole experience took about 45 minutes to be completed. Participants were instructed to react as quickly as possible as soon as they detected a change in the display by depressing the space bar of a standard keyboard with the index or middle finger of their dominant hand; they were also instructed to avoid errors. The instructions are presented on the screen at the beginning of the warm-up block and the experimental blocks. Participants were also instructed orally by the investigator. The warm-up block contained 4 no-go trials, 4 motion trials, 4 color trials and 12 redundant trials (2 trials per SOA: -200, -100, 100, 200[1] and 4 trials for SOA 0). After each trial of the warm-up (but not the experimental) block(s), feedback about the correctness of the participant's response was presented on the screen, but participants’ responses were not recorded. Each experimental block contained 28 no-go trials, 28 color trials, 28 motion trials and 28 redundant trials. At the beginning of each block a screen indicated the next block number and the participant had to press the space bar to initiate the block. Participants were free to take a break in the 57 trials. A total of 798 recorded trials were presented in a randomized order.

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[1] Larger SOAs for redundant targets were used in the warm-up block (than in the experimental blocks) to stress the possible time interval between feature changes.

3.3.2. Results

The results are reported in two parts; mean reaction times analyses were conducted to determine if there are redundancy gains and tests for violation of Miller's (1982, 1986) RMI were conducted to determine which type of processing model (parallel race vs. parallel coactive) fits best the observed data.

To avoid confounds by anticipatory and extremely slow responses, reaction times below 200 ms and above 1200 ms were exclude from analysis for all the subjects (note that the 1200 ms limit was chosen in function of the overall reaction time distributions). Extreme reaction times, namely reaction times more than 2.5 standard deviations of the mean, were also excluded for each single feature condition and for each SOA. Misses and false alarm rates corresponded to less than 10% of the trials. Participants never missed a target (see Table 3). All multiple comparisons were adjusted according to Bonferroni correction where necessary.

Table 3.1

Mean correct Reaction Times (RT) error rates for target types (and standard deviation) in Experiment 1a.

				Error rates (%)				Mean redundancy gains (ms)					
Target type		RT (ms)		Miss		Extremes		$\text{Gain}_{B\&C}$		$\text{Gain}_{M\&L}$		Gain_{Avg}	
Single defined targets													
	Motion	348.14	(32.92)	0.00	(0.00)	2.15	(0.88)						
	Color	365.66	(28.07)	0.00	(0.00)	1.93	(0.84)						
Redundant defined targets													
	-60ms	346.87	(27.87)	0.00	(0.00)	1.59	(1.88)	1.26	(8.47)	1.98	(9.16)	10.03	(8.10)
	-40ms	344.34	(36.96)	0.00	(0.00)	2.81	(1.59)	3.80	(6.92)	4.51	(6.60)	12.56	(8.80)
	-20ms	339.97	(28.79)	0.00	(0.00)	3.17	(2.15)	8.17	(12.71)	8.88	(13.94)	16.93	(10.20)
FCA	0ms	344.32	(26.48)	0.00	(0.00)	2.38	(2.53)	3.82	(10.71)	4.53	(12.15)	12.58	(8.19)
	20ms	355.19	(31.95)	0.00	(0.00)	1.21	(1.81)	-7.06	(10.98)	-6.34	(12.07)	1.71	(9.43)
	40ms	356.26	(24.96)	0.00	(0.00)	2.38	(2.53)	-8.12	(14.11)	-7.41	(14.99)	0.64	(12.85)
	60ms	360.12	(26.01)	0.00	(0.00)	2.40	(1.80)	-11.98	(10.08)	-11.27	(11.16)	-3.21	(7.17)
	Mean	349.58	(28.07)	0.00	(0.00)	2.28	(0.68)	-1.44	(7.08)	-0.73	(7.55)	7.32	(4.68)

Note. Mean reaction times redundancy gains are relative to the fastest single-feature ($\text{Gain}_{B\&C}$ and $\text{Gain}_{M\&L}$) and relative to the average of both single feature targets (Gain_{Avg}). $_{B\&C}$ = Biederman and Checkosky, 1970; $_{M\&L}$ = Miller and Lopes, 1988.

*Mean reaction times***.** The mean reaction times are presented in Table 3.1 and shown in Figure 3.2. RT analysis (a one-way ANOVA with the factor target type, i.e., color, orientation and redundant targets) showed a significant difference between target types ($F(2,18) = 45.25$, MS_e

= 20.92, $p < .001$); multiple comparisons revealed that motion trials (M = 348.1 ms, SD = 32.9 ms; $t(9) = 7.51$, $p < .001$) and redundant trials (M = 359.6 ms, SD = 28.1 ms; $t(9) = 11.10$, $p < .001$) were both responded to significantly faster than color trials (M = 365.7 ms, SD = 28.1 ms); motion and color trial RTs did not differ significantly from each other ($t(9) = .65$, $p < .10$). Further, a one-way ANOVA (with the factor SOA, i.e., SOA from -60 to + 60) revealed a significant main effect of SOA ($F(6,54) = 7.33$, $MS_e = 77.71$, $p < .001$), accompanied by linear ($F(1,9) = 44.09$, $MS_e = 50.28$, $p < .001$) and quadratic trends ($F(1,9) = 5.47$, $MS_e = 113.32$, $p < .05$). Multiple comparisons indicated no significant difference between adjacent SOAs (all $p < .10$). Finally, the fastest reaction times to redundantly defined targets was observed at SOA -20 ms, that is in trials in which the motion change occurred 20 ms before color change. This result contradicts Ulrich and Miller's (1997) prediction of optimal feature integration in conditions with synchronous change; it also provides a first piece of evidence of a difference in processing times for motion and color signals.

*Redundancy gains***.** The redundant targets were globally detected 7.3 ms faster than the average of the single targets ($Gain_{Avg}$). Biederman and Checkosky (1970) proposed that it might be assumed that all observers would respond preferentially to the same feature, in the present case the color feature. In this case, the redundancy gain is estimated by the difference between reaction times for targets defined by the preferred feature and for the redundantly defined targets for each participant. This *fixed-favored feature* test (referred to as $Gain_{B\&C}$) indicated a 1.44 ms redundancy cost (rather than gain) for redundant relative to non-redundatn feature changes. Biederman et al.'s conjecture might be incorrect, however; participants might show different preferences for features or none at all. To account for this possibility, Miller and Lopes (1988) compared the mean reaction times of the single targets at the level of individual participants. If single RTs differ significantly (on a liberal criterion of $\alpha = .10$), the faster reaction times is used for the redundancy gain analysis; if there is no RT difference between features, the overall mean reaction time from the two features is used as a comparison standard with redundant RTs; gains are referred to as $Gain_{M\&L}$. $Gain_{M\&L}$ was equal to an overall redundancy cost of 0.7 ms. The right-hand part of the Table 3.1 shows the redundancy gains for each SOA, corresponding to the mean RTs calculated by the procedures described above. Because it seems to be the most adequate procedure to determine redundancy gains, in the following analyses only results following the Miller and Lopes (1988) procedure are reported. A repeated measures ANOVA (with the factor SOA) of RT redundancy gains showed the same results as the repeated measure ANOVA for RT, namely a main effect of SOA ($F(6,54) = 7.33$, $MS_e = 77.71$, $p < .001$), accompanied by linear ($F(1,9)$ =

44.09, $MS_e = 50.28$, $p < .001$) and quadratic trends ($F(1,9) = 5.47$, $MS_e = 113.32$, $p < .05$). To test whether redundancy gains differed from 0, a one sample t-test was applied to redundancy gains of each SOA. Only in two SOA values a tendency of significant difference was found (SOA -40: $t(9) = 2.161$, $p = .059$ and SOA -20: $t(9) = 2.015$, $p = .075$; for all other SOA, $p > .10$).

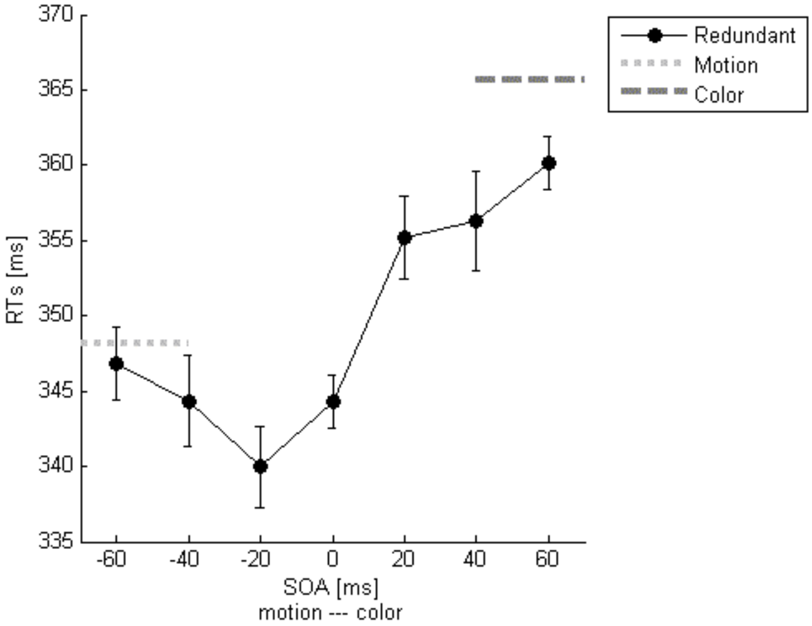


Figure 3.2. Mean RTs for the singly defined targets and for redundantly defined targets in function of the SOA in Experiment 1a. The solid line represents the mean RT (and standard error) for the redundant targets for each SOA. A negative SOA indicates that motion changed first, whereas a positive SOA signifies that color changed first. Dashed lines at each side of the figure indicate respectively the mean RT for the motion and color targets.

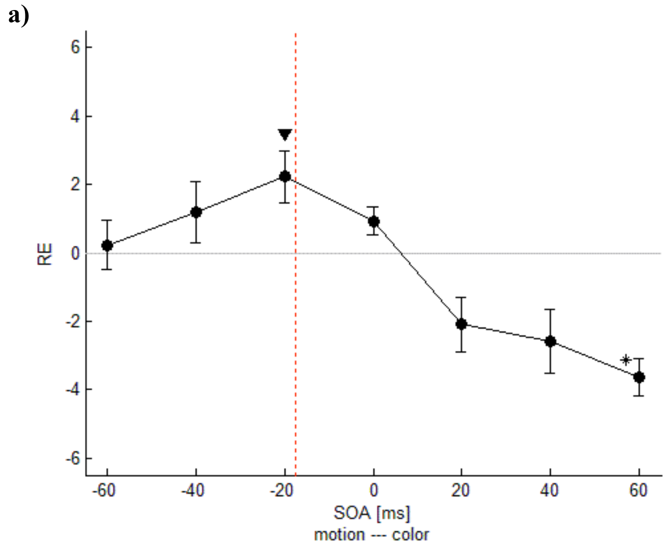
Overall, the results suggest that the motion has to occur between 0 and 40 ms before the color change to generate maximum redundancy gains. This finding seems to contradict Ulrich and Miller's (1997) prediction of optimal redundancy effects with synchronous changes. Note however, that this interpretation is qualified by the small redundancy gains ant the small differences between redundancy gains at SOAs of -40, -20 and 0 ms.

Physiological chronometry. Diederich and Colonius (2004) proposed a procedure determining the facilitatory effect of redundantly defined targets based on a method used by Meredith and Stein (1986) to investigate the multisensory response enhancement (MRE) or inhibition of neurons in superior colliculus to multisensory stimulation. The RE index is computed according to the following formula:

$$RE = \frac{\min(\overline{RT}_m, \overline{RT}_c) - \overline{RT}_{m\tau c}}{\min(\overline{RT}_m, \overline{RT}_c)} \times 100,$$

in which $\overline{RT}_m$ corresponds to the mean reaction time for targets defined by motion, $\overline{RT}_c$ to the mean reaction time for the targets defined by color and $\overline{RT}_{m\tau c}$ to the mean reaction time for redundantly defined targets. τ represents the time interval between the onset of the two stimuli (the SOA). For example, a MRE value of 10 indicates that a redundantly defined target at a given SOA is detected 10% faster than the fastest of the corresponding singly defined targets. According to Raab's (1962) "synchronicity" model, the largest facilitation should be predicted at the SOA closest to the difference between mean reaction times of the two singly defined targets as this difference reflects the supposed maximal overlap of the two underlying RT density distributions. Consequently, the maximal MRE would be expected close to the difference between single feature mean reaction times (Diederich & Colonius, 2004). Although, as predicted, the larger observed response enhancement (*M* = 2.2 , *SD* = 3.4 at SOA -20) is near the difference between reaction times for motion and color (-17.5 ms), it was marginally larger than 0 (one sample t-test: $t(9) = 2.08$, $p = .068$; see Figure 3.3).

RT distribution analysis. According to Miller (1982) an analysis of the entire RT distribution allows differentiating parallel co-active processing from strictly parallel processing of redundantly defined targets. As mentioned above, Miller (1982) proved that all models assuming strict parallel processing (features are processed independently and simultaneously) must not violate the following race model inequality (RMI): $F_R(t) \leq F_{T1}(t) + F_{T2}(t)$, where t is the time since display presentation and F the cumulative function of reaction times. T1 and T2 correspond to the features of the redundantly defined target R. The inequality assumes that in a strict parallel model the cumulative probability to detect a redundantly defined target at a certain time t after signal onset is equal or bigger than the sum of the cumulative probability to detect a target defined by one of both features composing the redundantly defined target plus the probability to detect a target defined by the other feature at this same time t after onset. Violations of the inequality provide evidence against strictly parallel processing. Miller (1986) proposed an extension of his (1982) inequality by allowing SOAs between features of a redundantly defined target: $F_R(t) \leq F_{T1}(t\text{-}SOA_{T1}) + F_{T2}(t\text{-}SOA_{T2})$, where SOA_{T1} and SOA_{T2} correspond to the time passed since display onset at which the redundantly defined target acquires its defining features. Because the change of one of the features corresponds to the measurement onset, the SOA for this feature is consequently set to 0.



b)

SOA	mean RE (%)	t(9)	sign
-60ms	0.23 (2.49)	0.29	.780
-40ms	1.18 (1.99)	1.87	.094
-20ms	2.22 (3.39)	2.08	.068
0ms	0.93 (2.78)	1.06	.316
20ms	-2.10 (3.05)	-2.18	.058
40ms	-2.59 (4.18)	-1.96	.082
60ms	-3.65 (3.11)	-3.71	.005 **

Figure 3.3. **Panel a**) Response enhancement (RE) as a function of SOA in Experiment 1a. The black line corresponds to RE for each SOA. A positive RE indicates a response enhancement, whereas a negative RE indicates a response inhibition. A positive SOA indicates that the color changed first, whereas a negative SOA indicates that motion changed first. The triangle represents the maximal observed RE whereas the vertical dashed line stood for the maximal predicted RE. Stars indicate that the RE is significantly different from 0 (represented by the grey horizontal line). **Panel b**) Mean RE (and standard deviation), as well as the one-sample t-test against 0, for each SOA (** corresponding to $p < .01$).

Using the same method as Krummenacher et al. (2001, 2002a, b), the summed cumulative function for singly defined targets was calculated for a set of response times, t, that corresponded to the 5% quantiles (5th, 10th, 15th, …, 95th quantile) of the response time distribution of redundantly defined targets. The RMI is violated if the summed cumulative function for color and sound targets is smaller than the cumulative function for the redundantly defined targets. Because RMI violations were already observed in visual search tasks (Krummenacher et al., 2001, 200a, b; s.a. Koene & Li, 2007; Poom, 2009), the significance level of a violation was computed with a one-tailed t-test for each quantile. This procedure showed that, although a single significant RMI violation was observed at SOA 60, motion and color were processed in a parallel coactive way when motion changed 40 ms before color (see Figure 3.4).

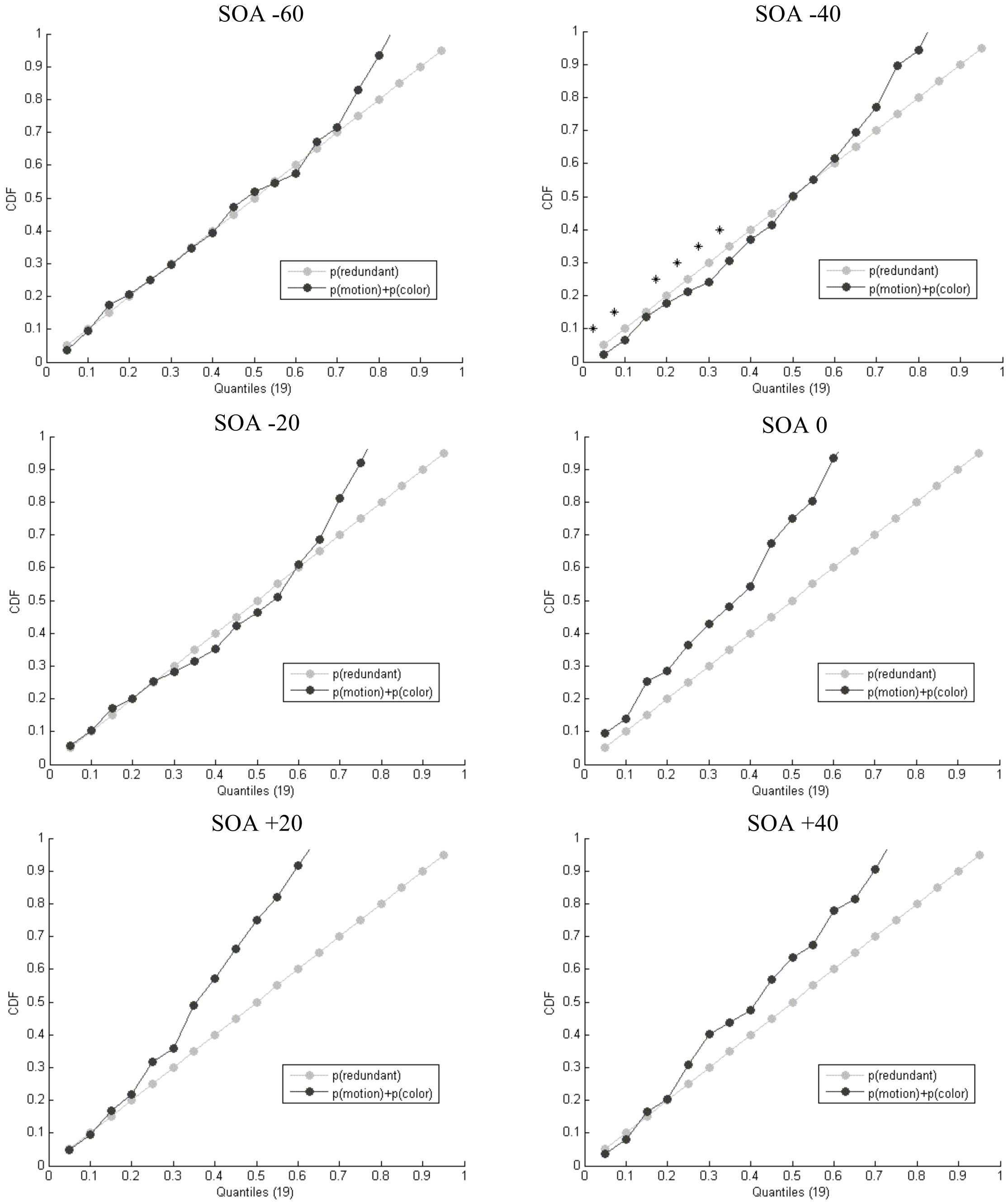


Figure 3.4. Results of the tests for violations of Miller's (1986) RMI in RTs of Experiment 1a according to the SOA. The dark grey curve represents the cumulative probability function for the summed probabilities of RTs to single targets having occurred at a given time t; the light grey curve represents corresponding redundant target probabilities. Significant violations are marked with a star ($p < .05$). Note that for the RMI to be satisfied, summed single dimension probabilities must be no smaller than redundant target probabilities.

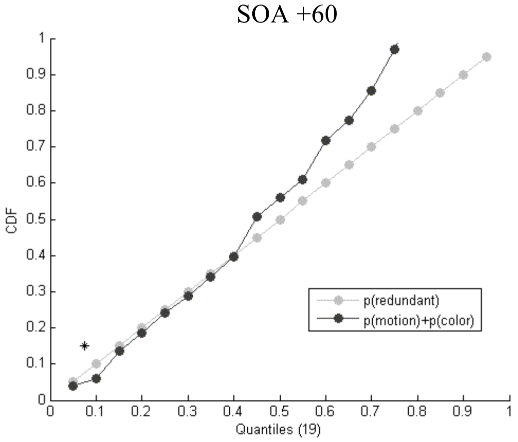


Figure 3.4 (continued).

Altogether, the four different tests used to determine the adequate underlying integration model indicated that signal integration is optimal, in terms of observed change detection RTs, when motion changed between 20 to 40 ms before color. The fastest reaction times, as well as the largest response enhancement and redundancy gain were observed at SOA -20, while a maximal number of RMI violations was found at SOA -40. These results are coherent with the assumption of perceptual lag between color and motion reported by Moutoussis and Zeki (1997a, b), in which motion requires more time to be perceived than color. Furthermore, the fact that RMI violations could be observed in this paradigm cannot be explained by Li's (2002; see also Koene & Li, 2007) V1 hypothesis claiming that RMI violations for redundant targets defined by motion and color are not possible because of a lack of motion-color tuned cells at the level of the primary visual cortex (V1). However, the present findings do not necessarily contradict Schönwälder's (2006) observation. For technical reasons, Schönwälder used longer SOAs (multiples of 28) than in the present study (multiples of 20). It is possible that Schönwäder's SOAs did not identify the optimal time point of integration.

3.4. Experiment 1b: Motion – orientation detection task

Experiment 1a showed that motion and color were best integrated when the motion change preceded the color change by 0 to 40 ms. Experiment 1b investigates the temporal integration of motion and orientation using the same paradigm. According to Moutoussis and Zeki's (1997b) findings, an optimal integration time point for motion and orientation features should be found when the motion change precedes the orientation change.

3.4.1. Method

Participants. Ten observers (7 female and 3 male) took part in Experiment 1b. All were students at the University of Fribourg. They were paid CHF 10. Their age ranged between 23 and 38 years (median = 27 years). All observers had normal or corrected to normal vision, including normal color vision.

Design, timing, procedure, apparatus and setting were identical to those used in Experiment 1a.

*Stimuli***.** Visual stimuli were 49 green vertical bars, each subtending 0.38° x 1.15° of visual angle that were presented on a grey background (RGB: 89, 89, 89). Because of the subjectively important difference between hues (e.g., Folk, Remington & Johnston, 1992), color isoluminance was not aimed at (RGB code for green: 0, 255, 0). Bars were displayed in the cells of a virtual 7x7 (rows x columns) matrix, subtending 13.56° x 14.25° of visual angle. The position of each item relative to the center of its matrix cell was randomly jittered in each trial (at a maximum distance of ±0.19° along the horizontal and vertical axes, respectively) to prevent collinearities with the other stimuli. During the trial all the elements moved horizontally (with a maximal amplitude of 1.15° of visual angle) to the left or the right with a speed determined by a sinusoidal function (α was set to 0 degree in the first frame and increased at each frame by 7 degrees). In no-go trials, none of the stimuli of the moving display changed, and the participants were instructed to refrain from responding and to wait for the next trial to begin. In go trials, either the orientation of one bar changed (orientation condition), or the motion direction (motion condition), or both the orientation and motion direction changed (redundant condition). In the orientation condition the orientation of one bar changed from 90° (vertical) to either 135° (left-tilted) or 45° (right-tilted); in the motion condition the bar moved along a virtual line diagonally tilted 62.25° to the left or right relative to vertical. In the redundant condition the feature change onsets were identical to the motion and color detection task of Experiment 1a.

3.4.2. Results

As for in the analysis of the previous Experiment 1a, anticipatory and extremely slow responses as well as extreme reaction times for each participant were excluded from analysis in Experiment 1b. Misses and false alarms represented less than 10% of the trials. There were no misses at all, that is, if a target was appeared, it was always detected (see Table 3.2).

Table 3.2

Mean correct RTs and error rates for target types (and standard deviation) in Experiment 1b.

				Error rates (%)				Mean redundancy gains (ms)					
Target type		RT (ms)		Miss		Extremes		$\text{Gain}_{B\&C}$		$\text{Gain}_{M\&L}$		Gain_{Avg}	
Single defined targets													
Motion		335.28	(25.98)	0.00	(0.00)	2.09	(1.09)						
Orientation		333.25	(27.25)	0.00	(0.00)	2.24	(0.91)						
Redundant defined targets													
FCA	-60ms	338.33	(32.43)	0.00	(0.00)	2.87	(2.82)	-5.07	(10.19)	-5.26	(9.13)	-4.06	(9.46)
	-40ms	332.28	(33.74)	0.00	(0.00)	1.79	(1.88)	0.97	(11.47)	0.79	(12.11)	1.98	(11.62)
	-20ms	330.50	(27.76)	0.00	(0.00)	2.54	(1.76)	2.75	(12.09)	2.57	(11.46)	3.76	(11.72)
	0ms	320.07	(24.42)	0.00	(0.00)	2.54	(1.75)	13.19	(11.46)	13.00	(11.42)	14.20	(11.13)
	20ms	328.27	(30.42)	0.00	(0.00)	1.81	(1.91)	4.98	(9.17)	4.80	(9.75)	5.99	(10.75)
	40ms	326.63	(24.04)	0.00	(0.00)	2.16	(1.86)	6.62	(7.11)	6.44	(7.78)	7.63	(6.98)
	60ms	332.65	(24.30)	0.00	(0.00)	3.21	(2.64)	0.60	(9.13)	0.42	(9.85)	1.61	(9.37)
	Mean	329.82	(26.69)	0.00	(0.00)	2.42	(0.53)	3.43	(3.10)	3.25	(3.39)	4.45	(3.25)

Note. Mean RT redundancy gains are relative to the fastest single-feature ($\text{Gain}_{B\&C}$ and $\text{Gain}_{M\&L}$) and relative to the average of both single feature targets (Gain_{Avg}). $_{B\&C}$ = Biederman and Checkosky, 1970; $_{M\&L}$ = Miller and Lopes, 1988.

*Mean RTs***.** The mean RTs of the motion and orientation change Experiment 1b are presented in Table 3.2 and shown in Figure 3.5. The RT analysis (one-way ANOVA with the factor target type: color, orientation and redundant targets) shows a significant difference between target types ($F(2,18) = 7.62$, $MS_e = 9.99$, $p < .005$); multiple comparisons indicate that targets in redundant trials ($M = 329.8$ ms, $SD = 26.7$ ms) were significantly faster processed than in motion ($M = 335.2$ ms, $SD = 26.0$ ms; $t(9) = 3.49$, $p < .05$) and orientation trials ($M = 333.2$ ms, $SD = 27.2$ ms; $t(9) = 3.50$, $p < .05$). However, motion and orientation targets did not differ significantly ($t(9) = 1.26$, $p > .10$). Moreover, as in the preceding Experiment 1a, a one-way ANOVA with the factor SOA showed a main effect of SOA ($F(6,54) = 2.93$, $MS_e = 110.63$, $p < .05$), accompanied by a significant quadratic effect ($F(1,9) = 12.55$, $MS_e = 152.26$, $p < .001$); multiple comparisons did not reveal significant differences between adjacent SOAs (all $p > .10$).

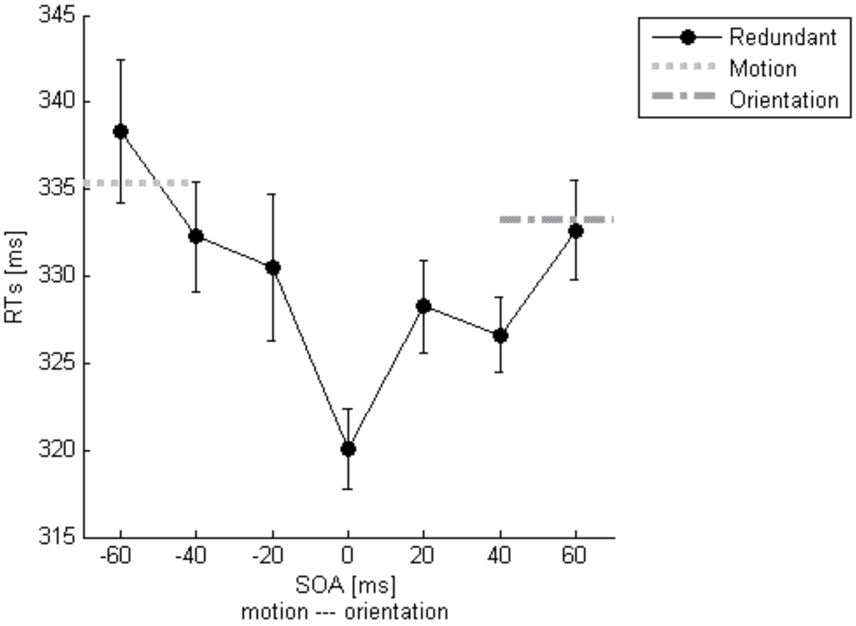
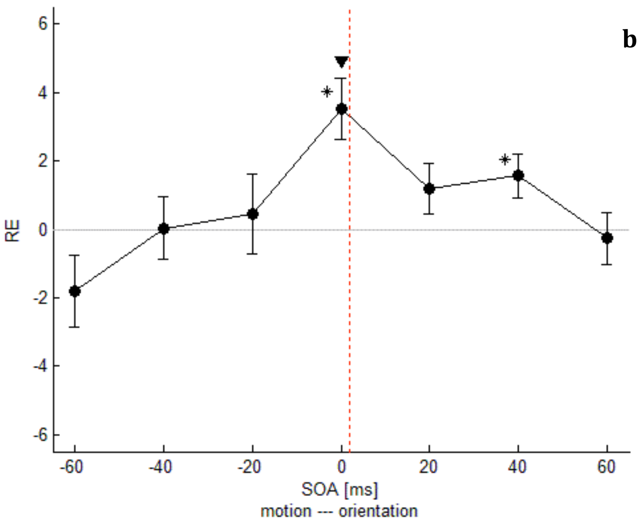


Figure 3.5. Mean RTs for the singly defined targets and for redundantly defined targets as a function of SOA in Experiment 1b. The solid line represents the mean RT (and standard error) for the redundant targets for each SOA. A negative SOA indicates that motion changed first, whereas a negative SOA signifies that orientation changed first. Dashed lines at each side of the figure indicate namely the mean reaction time for the motion and orientation targets.

*Redundancy gains and physiological chronometry***.** The redundant targets are detected 4.5 ms faster than the average of the single targets (Gain$_{\text{Avg}}$). Testing for Gains$_{\text{B\&C}}$ revealed a redundancy effect of 3.4 ms, whereas Gains$_{\text{M\&L}}$ were of 3.3 ms. A one-factor repeated measures ANOVA (with the factor SOA) showed the same results as the ANOVA for reaction times, a significant main effect of SOA ($F(6,54) = 2.93$, $MS_e = 110.63$, $p < .05$). A one sample t-tests on Gains$_{\text{M\&L}}$ redundancy gains show gains significantly different from 0 at SOAs 0 and 40 (respectively, $t(9) = 3.60$, $p < .01$, and $t(9) = 2.62$, $p < .05$). MRE (response enhancement) analysis confirmed that the maximal enhancement ($M = 3.5$, $SD = 3.3$ for SAO 0) is observed close to the difference between reaction times to singly defined targets, namely at SOA 20 ms (see Figure 3.6). Further, in contrast to MRE analysis of Experiment 1a, the maximal response enhancement is significantly larger than 0 ($t(9) = 3.37$, $p < .01$).

*RT distribution analysis***.** In contrast to the motion-color paradigm, a larger number of SOAs provoked (few but) significant RMI violations. The cumulative function for redundant targets is significantly higher than the summed cumulative function of orientation and motion at quantile 5 for SOAs -60 and 0 ms, at quantile 10 for SOAs 20 and 40 ms, and at quantiles 10 and 15 for the SOA -40 (see Figure 3.7).

a)



b)b

SOA	mean RE (%)		t(9)	sign
-60ms	-1.80	(2.67)	-2.13	.062
-40ms	0.03	(3.51)	0.03	.976
-20ms	0.44	(3.50)	0.39	.703
0ms	3.52	(3.31)	3.37	.008 **
20ms	1.18	(3.00)	1.25	.244
40ms	1.56	(2.11)	2.34	.044 *
60ms	-0.27	(2.75)	-0.31	.764

Figure 3.6. **Panel a**) Response enhancement (RE) as a function of SOA in Experiment 1b. The black line corresponds to RE for each SOA. A positive RE indicates a response enhancement, whereas a negative RE indicates a response inhibition. A positive SOA indicates that the orientation changed first, whereas a negative SOA indicates that motion changed first. The triangle represents the maximal observed RE whereas the vertical dashed line stood for the maximal predicted RE. Stars indicate that the RE is significantly different from 0 (represented by the grey horizontal line). **Panel b**) Mean RE (and standard deviation), as well as the one-sample t-test against 0 for each SOA.

To sum the findings of Experiment 1b, although RMI violations were observed for five SOAs out of seven, mean reaction times, redundancy gains and physiological chronometry analyses lead to the conclusion that motion and orientation were at best integrated when both features changed synchronously. This finding agrees with the prediction of Ulrich and Miller's (1997) mathematical model. Furthermore, in contradiction with Moutoussis and Zeki (1997b) who had reported a perceptual processing advantage for orientation on motion, the present result suggests that, when motion and orientation are integrated, they are processed at the same speed.

3.5. Experiment 1c: Color – orientation detection task

Experiment 1c investigated the temporal integration of the last pair of features, namely color and orientation. Previous researches (Krummenacher et al., 2001, 2002a, b; see also Koene & Li, 2007) already demonstrated violations of Miller's (1982) RMI with synchronous feature onsets. However, according to Moutoussis and Zeki (1997b), color signals are processed faster than orientation signals, suggesting that the optimal temporal feature integration should occur when orientation changes before color.

3.5.1. Method

Participants. 12 observers (6 female and 6 male) took part in Experiment 1c. All were students at the University of Fribourg. They received 3 credits of experience or were paid 10Fr CH. They were aged between 21 and 25 year old (median = 22.5). Eleven of the observers had a normal or a correct-to-normal vision, including normal vision color.

Design, timing, procedure, apparatus and setting were identical as those used in Experiment 1a.

*Stimuli***.** Visual stimuli were 49 green vertical bars, each subtending 0.38° x 1.15° of visual angle that were presented on a grey background (RGB: 89, 89, 89). Because of the subjectively important difference between hues (e.g., Folk, Remington & Johnston, 1992), color isoluminance was not aimed at (RGB code for green: 0, 255, 0). Bars were displayed in the cells of a virtual 7x7 (rows x columns) matrix, subtending 13.56° x 14.25° of visual angle. The position of each item relative to the center of its matrix cell was randomly jittered in each trial (at a maximum distance of ±0.19° along the horizontal and vertical axes, respectively) to prevent collinearities with the other stimuli. In no-go trials, none of the stimuli changed, and the participants were instructed to refrain from responding and to wait for the next trial to begin. In go trials, either the color (color condition), or the orientation of one bar changed (orientation condition), or both the color and orientation direction changed (redundant condition). In the color condition, the color of one bar changed from green to red (RGB code: 255, 0, 0) or blue (RGB code: 0, 0, 255); In the orientation condition, the orientation of one bar changed from 90° (vertical) to either 135° (left-tilted) or 45° (right-tilted). In the redundant condition, the feature change onsets were identical to the motion and color detection task of Experiment 1a.

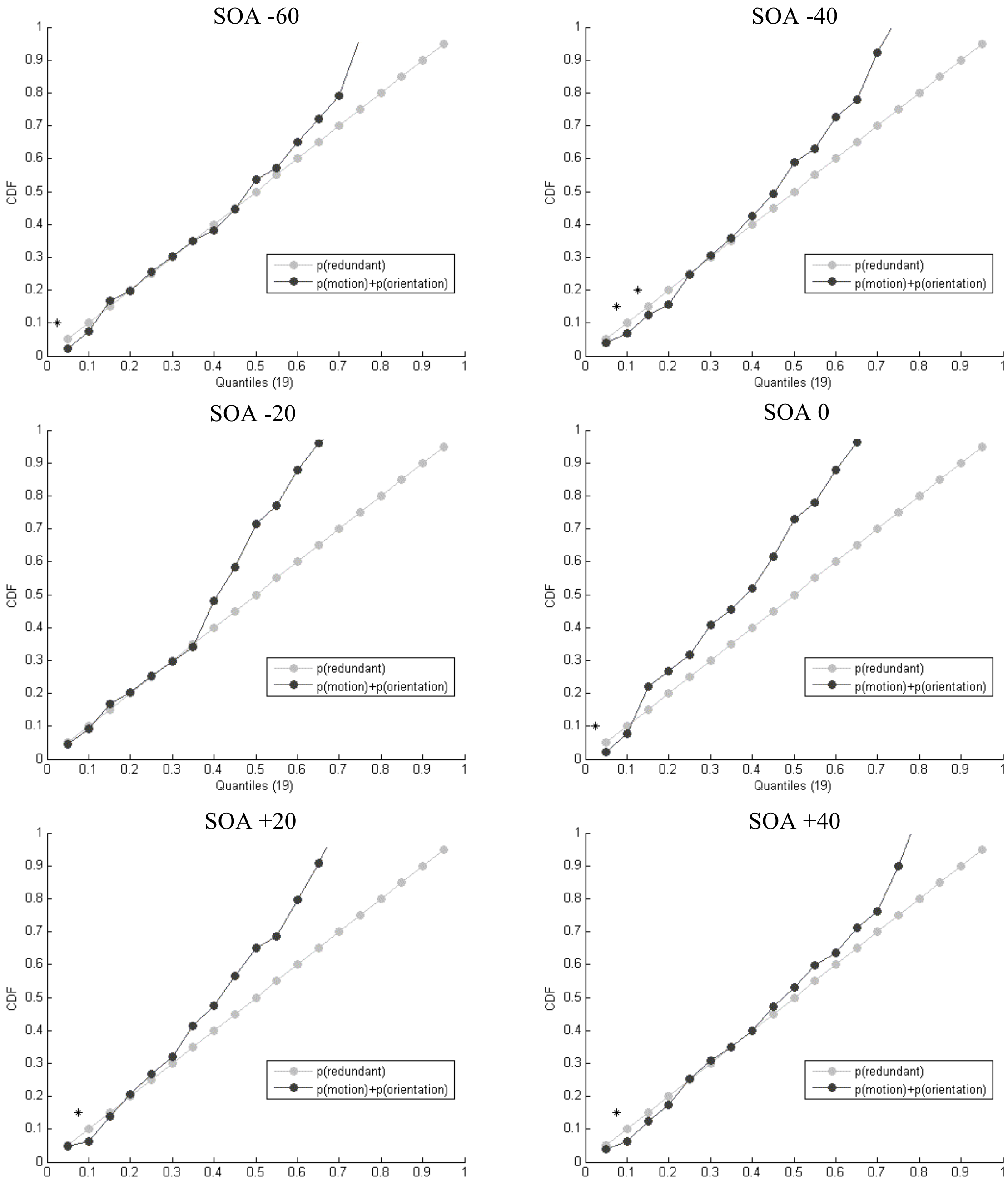


Figure 3.7. Results of the tests for violations of Miller's (1986) RMI in RTs of Experiment 1b according to the SOA. The dark grey curve represents the cumulative probability function for the summed probabilities of RTs to single targets having occurred at a given time t; the light grey curve represents corresponding redundant target probabilities. Significant violations are marked with a star ($p < .05$). Note that for the RMI to be satisfied, summed single dimension probabilities must be no smaller than redundant target probabilities.

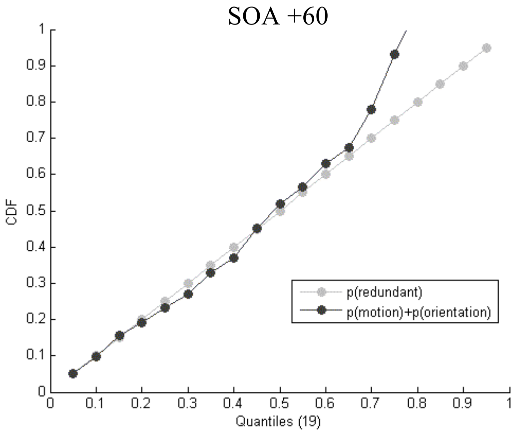


Figure 3.7 (continued).

3.5.2. Results

As in the previous Experiments 1a and 1b, anticipatory and extremely slow responses, as well extreme reaction times were excluded from. Misses and false alarms corresponded to less than 10% of the trials. A one-way repeated-measures ANOVAs with the factor target type did not indicate any significant differences in error rates between singly defined targets or redundantly defined targets ($F(1.50,16.42) = .682$, $MS_e = .02$, $p > .10$; Huynh-Feldt-corrected degrees of freedom); an ANOVA of error rates of the different SOAs did not reveal any significant effects, either ($F(1,11) = .10$, $MS_e = .98$, $p > .10$).

Table 3.3

Mean correct reaction times (RT) for target types of detection task in Experiment 1c.

				Error rates (%)				Mean redundancy gains (ms)					
Target type		RT (ms)		Miss		Extremes		$\text{Gain}_{B\&C}$		$\text{Gain}_{M\&L}$		Gain_{Avg}	
Single defined targets													
Color		323.93	(40.63)	0.09	(0.20)	2.30	0.705						
Orientation		303.91	(35.38)	0.17	(0.45)	2.30	0.705						
Redundant defined targets													
FCA	-60ms	316.67	(35.99)	0.00	(0.00)	2.71	(1.64)	-12.76	(9.17)	-12.76	(9.17)	-2.75	(8.87)
	-40ms	319.01	(36.57)	0.00	(0.00)	3.00	(2.07)	-15.10	(6.66)	-15.10	(6.66)	-5.09	(7.77)
	-20ms	313.81	(38.29)	0.31	(1.07)	2.41	(1.78)	-9.91	(7.14)	-9.91	(7.14)	0.10	(5.00)
	0ms	301.98	(33.58)	0.00	(0.00)	2.44	(1.80)	1.93	(7.38)	1.93	(7.38)	11.94	(7.16)
	20ms	300.86	(35.71)	0.00	(0.00)	3.01	(1.41)	3.05	(8.92)	3.05	(8.92)	13.06	(9.88)
	40ms	304.19	(37.68)	0.00	(0.00)	3.30	(1.84)	-0.28	(10.35)	-0.28	(10.35)	9.73	(11.03)
	60ms	302.81	(38.15)	0.00	(0.00)	2.39	(1.77)	1.10	(7.58)	1.10	(7.58)	11.11	(8.08)
	Mean	308.48	(35.82)	0.04	(0.15)	2.65	(0.37)	-4.57	(3.47)	-4.57	(3.47)	5.44	(3.89)

Note. Mean RT redundancy gains are relative to the fastest single-feature ($\text{Gain}_{B\&C}$ and $\text{Gain}_{M\&L}$) and relative to the average of both single feature targets (Gain_{Avg}). $_{B\&C}$ = Biederman and Checkosky, 1970;. $_{M\&L}$ = Miller and Lopes, 1988.

*Mean RTs***.** The mean RTs are presented in Table 3.3. The results show a significant difference between the target types ($F(1.423,15.65) = 65.74$, $MS_e = 28.26$, $p < .001$; Huynh-Feldt corrected degrees of freedom); multiple comparisons indicate that orientation targets ($M = 303.9$ ms, $SD = 35.8$ ms) were processed significantly faster than redundant trials ($M = 308.5$ ms, $SD = 40.6$ ms; $t(11) = 4.57$, $p < .01$), redundant targets were processed significantly faster than color trials ($M = 323.9$ ms, $SD = 35.4$ ms; $t(11) = 7.70$, $p < .001$). Moreover, similarly to the Experiments 1a and 1b using motion, a a one-way repeated measures ANOVA of redundant target RTs with the factor SOA showed a significant main effect of SOA ($F(6,66) = 10.88$, $MS_e = 65.69$, $p < .001$), accompanied by significant linear ($F(1,11) = 36.66$, $MS_e = 78.55$, $p < .05$) and quadratic effects ($F(1,11) = 14.48$, $MS_e = 20.4$, $p < .01$); multiple comparisons showed a significant difference between RTs to redundant targets at adjacent SOAs -20 and 0 ($t(11) = 4.46$, $p < .05$, all other, $p > .10$; see Figure 3.8).

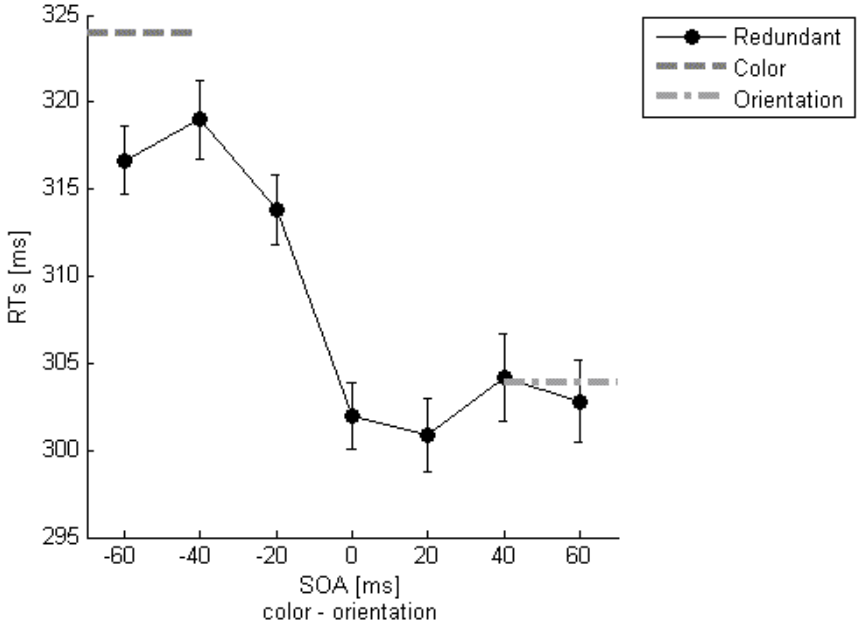
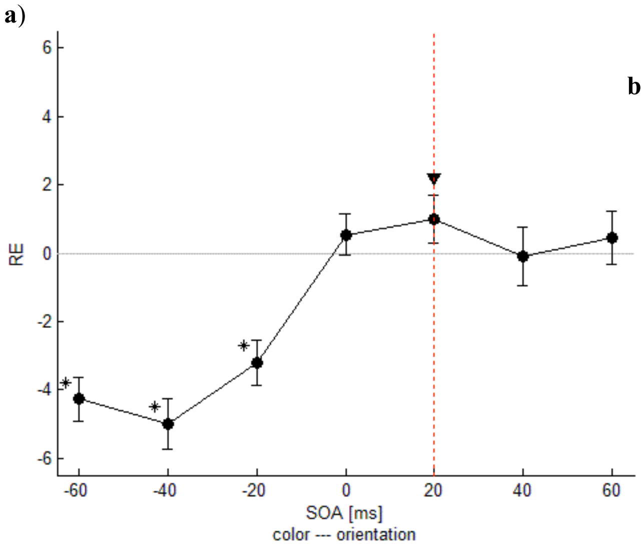


Figure 3.8. Mean RTs for the singly defined targets and for redundantly defined targets as a function of SOA in Experiment 1c. The solid line represents the mean RT (and standard error) for the redundant targets for each SOA. A negative SOA indicates that color changed first, whereas a negative SOA signifies that orientation changed first. Dashed lines at each side of the figure indicate namely the mean RT for the color and orientation targets. The star indicates a significant reaction times difference between adjacent SOAs ($p < .05$).

Redundancy gains and physiological chronometry. Redundant targets are detected 5.4 ms faster than the average of the single targets ($Gain_{Avg}$). Tests for Biederman and Checkosky (1970) and Miller and Lopes (1988) gains provide same result, namely a redundancy cost of -

4.6 ms. In Experiment 1c, in terms of RTS, all observers preferred single orientation to single color targets. The one-way repeated measures ANOVA (with the factor SOA) of the Miller and Lopes redundancy gains showed the same results as the ANOVA for reaction times, namely a significant main effect of SOA ($F(6,66) = 10.88$, MS$_e = 65.69$, $p < .001$). One sample t-tests (against 0) showed significant redundancy costs when color precedes orientation (SOA -60: $t(11) = -4.82$, $p = .001$; SOA -40: $t(11) = -7.86$, $p < .001$; SOA -20: $t(11) = -4.8$, $p = .001$). As in both preceding Experiments 1a and 1b, the response enhancement (MRE) test confirms that the maximal enhancement for color-orientation targets (*M* = .99, *SD* = 2.89) is close to the difference between single color and orientation RTs (20 ms) (see Figure 3.9). However, maximum enhancement was not significantly larger than 0 ($t(11) = 1.18$, .$p > .10$).



b)

SOA	mean RE (%)	t(11)	sign
-60ms	-4.28 (2.96)	-5.00	.000 ***
-40ms	-4.99 (2.25)	-7.68	.000 ***
-20ms	-3.22 (2.28)	-4.90	.000 ***
0ms	0.54 (2.38)	0.79	.447
20ms	0.99 (2.89)	1.18	.261
40ms	-0.09 (3.36)	-0.09	.930
60ms	0.44 (2.52)	0.61	.557

Figure 3.9. **Panel a**) Response enhancement (RE) as a function of SOA in Experiment 1c. The black line corresponds to RE for each SOA. A positive RE indicates a response enhancement, whereas a negative RE indicates a response inhibition. A positive SOA indicates that the orientation changed first, whereas a negative SOA indicates that color changed first. The triangle represents the maximal observed RE whereas the vertical dashed line stood for the maximal predicted RE. Stars indicate that the RE is significantly different from 0 (represented by the grey horizontal line). **Panel b**) Mean RE (and standard error), as well as the one-sample t-test against 0 for each SOA.

Reaction time distribution analysis. Reaction times distribution analyses showed only one violation of Miller's (1986) RMI, namely at quantile 10 when orientation changed 60ms before color ($t(11) = 2.26$, $p = 0.02$) (see Figure 3.10).

Altogether, the present results did not determine an explicit optimal integration point. Mean RTs, redundancy gain and physiological chronometry analyses indicated that color and orientation were best integrated when orientation changed 20 ms before color; however, the distribution analyses revealed only one RMI violation when orientation changed 60ms before color. The fact that changes in the orientation signal preceding color changes did not affect detection time of redundantly defined targets ($F(2,22) = .48$, $MS_e = 70.90$, $p > .05$) suggests that color-orientation integration is optimal in terms of detection RTs when orientation changes before color.

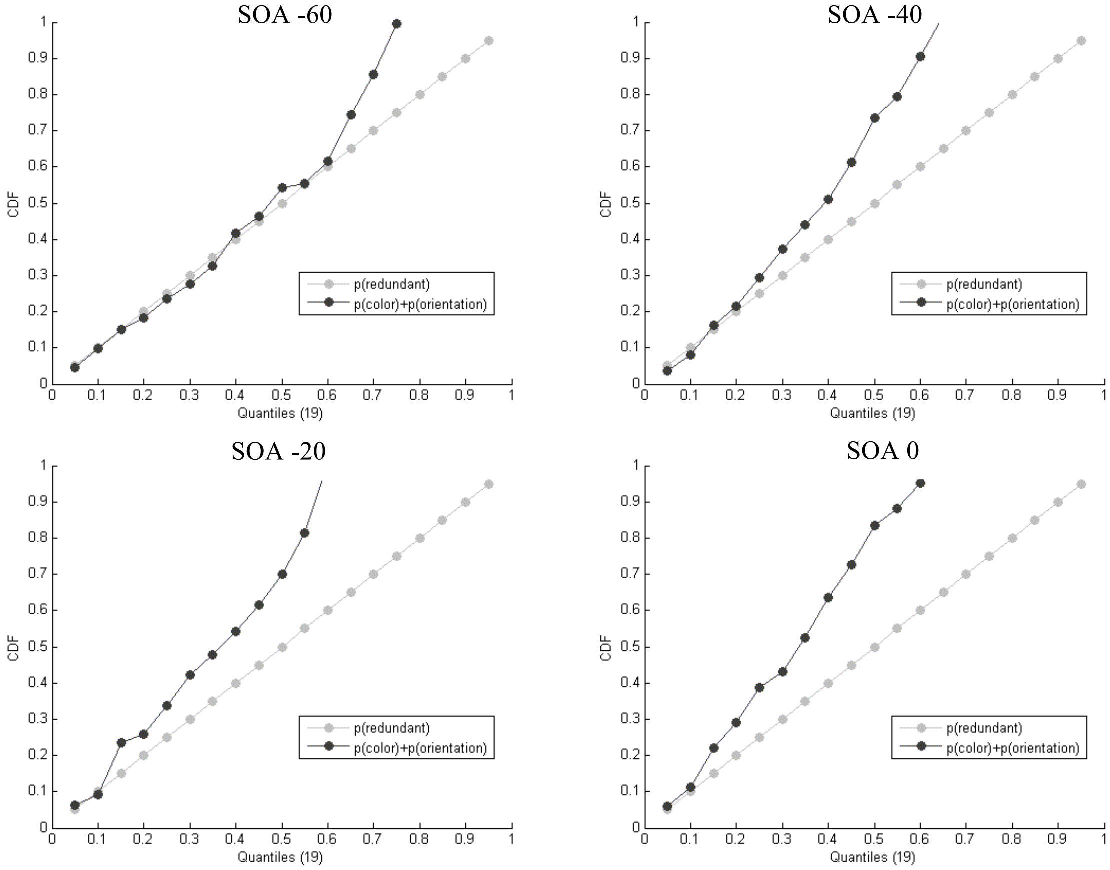


Figure 3.10. Results of the tests for violations of Miller’s (1986) RMI in RTs of Experiment 1c according to the SOA. The dark grey curve represents the cumulative probability function for the summed probabilities of RTs to single targets having occurred at a given time t; the light grey curve represents corresponding redundant target probabilities. Significant violations are marked with a star ($p < .05$). Note that for the RMI to be satisfied, summed single dimension probabilities must be no smaller than redundant target probabilities.

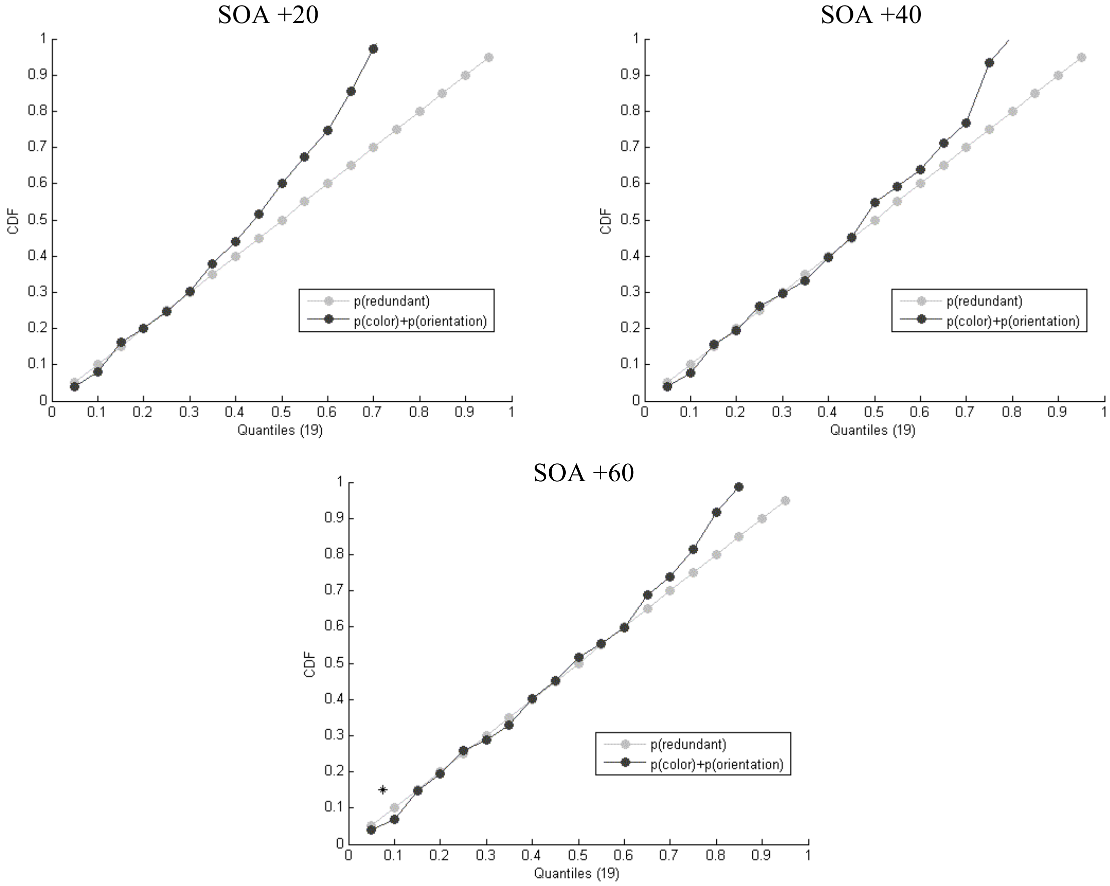


Figure 3.10 (continued).

3.6. Task comparison and discussion

Altogether, the results of Experiments 1a to c suggest that the optimal time for feature integration in a detection task depends on the combination of features to be bound together. In motion-color trials, the fastest detection for redundantly defined targets was obtained when motion changed around 0 to 40 ms before color; in motion-orientation trials, the best integration was with synchronous changes; finally, in the orientation-color condition, orientation preceding color produced the fastest RTs. Comparing the three different conditions it is obvious that they do not overlap (see Figure 3.11). Although all three integration curves show a (rough) V-shape, their position on the y-axis of the RT function is shifted relative to each other. Color and orientation feature integration was achieved faster than motion and orientation and also motion and color (significant one-way ANOVA of the grand mean RTs with the factor paradigm: $F(2,29) = 4.86$, $MS_e = 952.90$, $p < .05$). Multiple comparisons indicated a significant difference between color-orientation and motion-color conditions (*t*(20) = 2.95, *p* < .05), but not color-orientation and motion-orientation (*t*(20) = 1.56, *p* > .10) or motion-orientation and motion-color (*t*(18) = 1.61, *p* > .10) conditions.

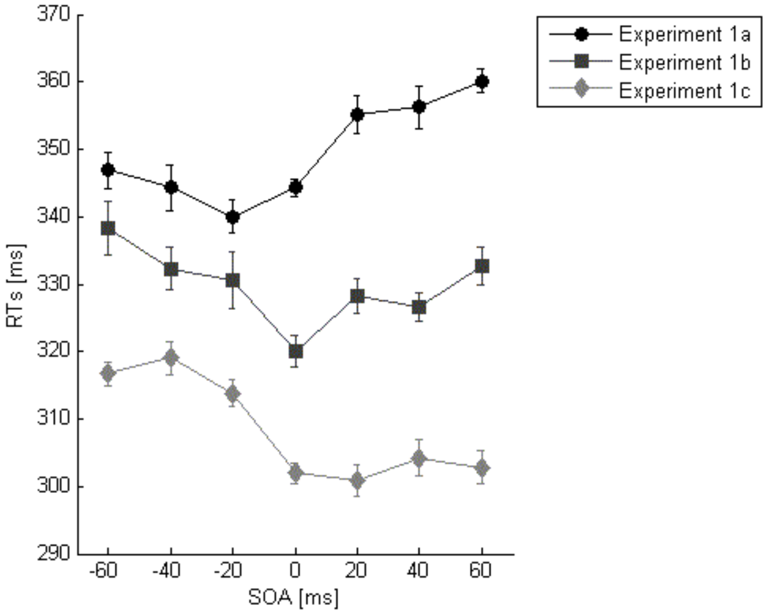


Figure 3.11. Detection task comparison of Experiment 1. The upper line (circles) stands for mean RTs (and standard error) for the redundant targets at each SOA in Experiment 1a (motion-color paradigm). The line in the middle (squares) represents results for Experiment 1b (orientation-motion paradigm), whereas the lower line (diamonds) represents results of Experiment 1c (color-orientation paradigm). A negative SOA indicates the time interval between the change of the first feature (indicated in the paradigm name) and the other feature change, whereas a positive SOA means an opposite feature change order.

The fact that different feature combinations produced distinct RT patterns seems to support the idea that the integration process in a detection task depends on the involved features. Identical color changes were not similarly fast detected when associated with a change of motion versus orientation. This finding can be explained by the fact that features are not processed in a strictly parallel fashion, as assumed by race models (e.g., Raab, 1962) and activation summation models (e.g., Miller, 1982, 1986); rather, there seems to be a cross-talk between channels that influences the processing of the other feature (see the interchannel crosstalk hypothesis of Mordkoff and Yantis, 1991). To test the cross-talk hypothesis, RTs for each feature (color, orientation, motion) were compared across conditions. If feature processing is strictly parallel, the detection time for a single feature target should not be influenced by the respective other feature. However, results of the tests demonstrate that single color or orientation targets were detected faster in the color-orientation condition than if either of them was associated with a motion-defined target (color: *t*(20) = 2.73, *p* < .05, orientation: *t*(20) = 2.14, *p* < .05, see Table 3.4 for mean RTs). On the other hand, although reaction times for targets singly defined by motion in the motion-color condition were higher than those of the motion-orientation condition, the difference did not reach significance (*t*(18) = .97, *p* > .10). These results therefore fit partially with the inter-channel cross-talk hypothesis, because only color and orientation were affected by the condition. The fact that a change of the condition (i.e., feature association) did not significantly affect the detection time for motion targets could lead to another hypothesis. One might assume that this observation is due to the motion of the whole visual display. In the conditions involving motion, all display elements moved in a sinusoidal fashion, whereas in the color-orientation condition, elements remained static. If motion induces an overall RT increase, RTs for targets defined either by color or orientation should be equivalent to those observed in the motion-color and motion-orientation conditions. However, if the color or orientation RTs exceed those observed in both conditions with motion as one target defining feature, this would suggest that the irrelevant motion interferes with the processing of both other target features; consequently, this would speak in favor of inter-channel crosstalk. In order to test this assumption a color-orientation detection task in which all items moved in a sinusoidal fashion was conducted (Experiment 1d).

Table 3.4

Mean RTs (with standard deviation) for singly defined targets in function of the paradigm.

Singly defined target	**Paradigm**	**Mean RT**	
Color	Motion-color	365.66	(28.07)
	Color-orientation	323.93	(40.63)
Orientation	Motion-orientation	333.25	(27.25)
	Color-orientation	303.91	(35.38)
Motion	Motion-color	348.14	(32.92)
	Motion-orientation	335.28	(25.98)

3.7. Experiment 1d: Dynamic color-orientation detection task

3.7.1. Method

Participants. Ten observers (all female) took part in Experiment 1d. All were students at the University of Fribourg. They were paid 10Fr CH and were aged between 21 and 25 year old (median = 22). All observers had a normal or a correct-to-normal vision, including normal vision color.

Design, timing, apparatus, setting and procedure were identical as those used in Experiment 1c.

Stimuli. Stimuli were identical to those used in the color-orientation condition of Experiment 1c with the only exception that all stimuli of the search display moved sinusoidal on a horizontal path (as in the conditions involving motion (according to a sinusoidal function with a maximal amplitude of 1.15° of visual angle and an increase of α by 7° per frame).

Table 3.5

Mean correct RTs for target types of detection task in the motion-orientation paradigm in Experiment 1c.

			Error rates (%)		Mean redundancy gains (ms)		
Target type		RT (ms)	Miss	Extremes	Gain$_{B\&C}$	Gain$_{M\&L}$	Gain$_{Avg}$
Single defined targets							
Color		387.84 (15.71)	0.00 (0.00)	2.61 (0.74)			
Orientation		375.81 (25.41)	0.11 (0.34)	2.61 (0.74)			
Redundant defined targets							
	-60ms	386.16 (18.92)	0.00 (0.00)	3.19 (1.20)	-10.35 (27.45)	-13.35 (22.31)	-4.33 (21.51)
	-40ms	384.40 (19.39)	0.00 (0.00)	2.40 (2.53)	-8.59 (15.95)	-11.59 (10.28)	-2.57 (9.68)
	-20ms	380.90 (21.74)	0.00 (0.00)	3.57 (1.79)	-5.09 (21.66)	-8.09 (18.29)	0.92 (16.60)
FCA	0ms	378.54 (17.62)	0.00 (0.00)	2.40 (1.80)	-2.73 (16.08)	-5.73 (9.83)	3.29 (9.445)
	20ms	367.11 (22.91)	0.00 (0.00)	2.40 (1.80)	8.70 (13.48)	5.70 (13.09)	14.72 (10.91)
	40ms	379.40 (17.12)	0.00 (0.00)	2.43 (1.82)	-3.59 (16.61)	-6.59 (11.24)	2.42 (11.55)
	60ms	372.41 (19.95)	0.00 (0.00)	2.78 (2.38)	3.40 (14.06)	0.40 (9.91)	9.41 (10.41)
	Mean	378.42 (16.12)	0.00 (0.00)	2.74 (0.68)	-2.61 (14.53)	-5.61 (8.59)	3.41 (7.25)

Note. Mean RT redundancy gains are relative to the fastest single-feature (Gain$_{B\&C}$ and Gain$_{M\&L}$) and relative to the average of both single feature targets (Gain$_{Avg}$). $_{B\&C}$ = Biederman and Checkosky, 1970;. $_{M\&L}$ = Miller and Lopes, 1988.

3.7.2. Results

As for the previous Experiments 1a to 1c, anticipatory and extremely slow responses, as well as extreme reaction times were excluded from analysis. Misses and false alarms correspond to less than 10% of the trials. A one way repeated-measures ANOVAs of error rates with the factor target type did not reveal any significant differences between singly defined targets and redundantly defined targets (*F*(1,9) = 1, MS_e = .077, *p* > .10; Huynh-Feldt-corrected degrees of freedom), there was no differences between different SOAs, either (all *p* > .10).

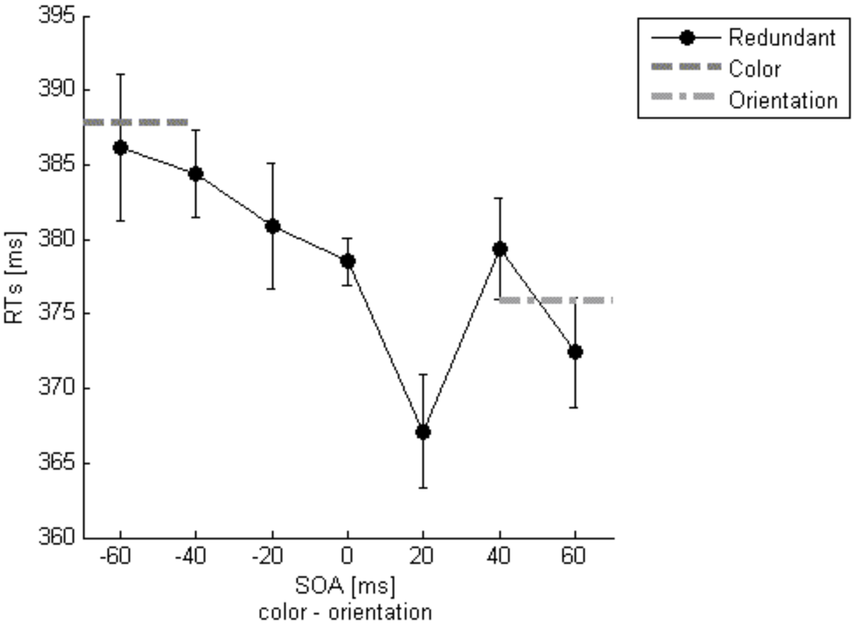
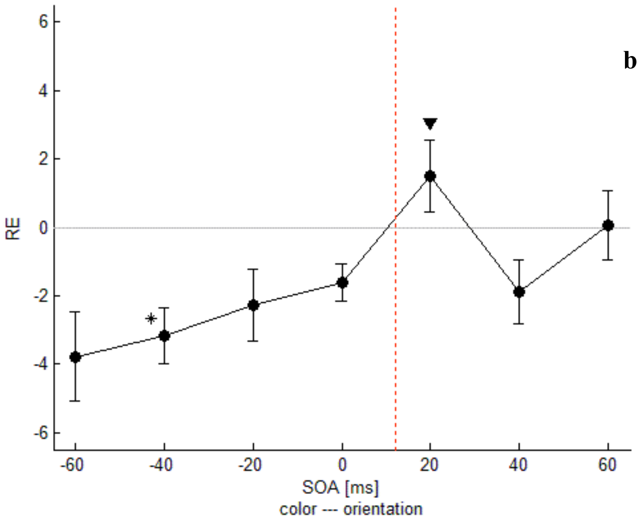


Figure 3.12. Mean reaction times for the singly defined targets and for redundantly defined targets in function of the SOA in Experiment 1d. The solid line represents the mean reaction time (and standard error) for the redundant targets for each SOA. Dashed lines at each side of the figure indicate namely the mean reaction time for the color and orientation targets.

Mean RTs. The mean RTs are presented in Table 3.5 and shown in Figure 3.12. A repeated measures ANOVA of RTs with the factor target type showed a significant difference between target types (*F*(1.20,10.80) = 4.82, MS_e = 138.68, *p* < .05; Huynh-Feldt-corrected degrees of freedom); multiple comparisons indicated that redundant targets (*M* = 378.4 ms, *SD* = 16.1 ms) were processed significantly faster than color targets (*M* = 387.8 ms, *SD* = 15.7 ms; *t*(9) = 5.92, *p* < .001), whereas reaction times for orientation targets (*M* = 375.8 , *SD* = 25.4) did not differ significantly from color (*t*(9) = 2.35, *p* > .10) or redundant targets (*t*(9) = .57, *p* > .10). Moreover, similarly to the Experiments 1a to 1c there was a main effect of SOA in redundant target trials (one-way ANOVA with the factor SOA: $F(6,54) = 2.92$, $MS_e = 152.29$, $p < .05$), accompanied by a significant linear effect ($F(1,9) = 5.52$, $MS_e = 273.28$, $p < .05$). Multiple comparisons showed no significant differences between adjacent SOAs (all $p > .10$).

a)



b)

SOA	mean RE (%)	t(11)	sign
-60ms	-3.78 (5.99)	-2.00	.077
-40ms	-3.18 (2.81)	-3.57	.006 **
-20ms	-2.27 (4.71)	-1.53	.161
0ms	-1.62 (2.60)	-1.97	.080
20ms	1.50 (3.46)	1.37	.203
40ms	-1.87 (3.17)	-1.87	.095
60ms	0.06 (2.71)	0.07	.947

Figure 3.13. **Panel a**) Response enhancement (RE) as a function of SOA in color-orientation detection task of Experiment 1. The black line corresponds to RE for each SOA. A positive RE indicates a response enhancement, whereas a negative RE indicates a response inhibition. A positive SOA indicates that the orientation changed first, whereas a negative SOA indicates that color changed first. The triangle represents the maximal observed RE whereas the vertical dashed line stood for the maximal predicted RE. Stars indicate that the RE is significantly different from 0 (represented by the grey horizontal line). **Panel b**) Mean RE (and standard error), as well as the one-sample t-test against 0, for each SOA.

Redundancy gains and physiological chronometry. The redundant targets are detected 3.4 ms faster than the average of the single targets ($Gain_{Avg}$), whereas Biederman and Checkosky (1970) and Miller and Lopes (1988) procedures provide opposite results, namely costs of 2.6 ms and 5.6 ms respectively. Like in the static color-orientation Experiment 1c, observers prefer orientation to color targets in terms of RTs (although the difference is not statistically reliable). A one-way repeated measures ANOVA (with the factor SOA) of the RTs obtained by application of the Miller and Lopes (1988) procedure showed the same results as the ANOVA for reaction times, namely a significant main effect of SOA ($F(6,54) = 2.92$, $MS_e = 152.29$, $p < .05$). One sample t-tests on the Miller and Lopes redundancy gains revealed a single significant redundancy cost when color precedes orientation by 40 ms ($t(9) = -3.57$, $p = .01$, see panel b of Figure 3.13). Response enhancement (MRE) analyses confirmed again that the maximal enhancement for dynamic color-orientation targets ($M = 1.50$, $SD = 3.46$) was closer to the difference between single color and orientation reaction times (see Figure 3.13).

However, as in the static color-orientation experiment, the difference did not reach statistical significance (*t*(9) = 1.37, *p* > .10).

Reaction times distribution analysis. The distributions analysis revealed violations of Miller's (1986) RMI for three different SOAs. One violation was observed at quantile 5 when orientation changed 20 ms before color, two violations at quantiles 5 and 10 when color changed 40 ms before orientation, whereas, when color changed 60 ms before orientation, three RMI violations (at quantiles 5, 10 and 15) were observed (see Figure 3.14).

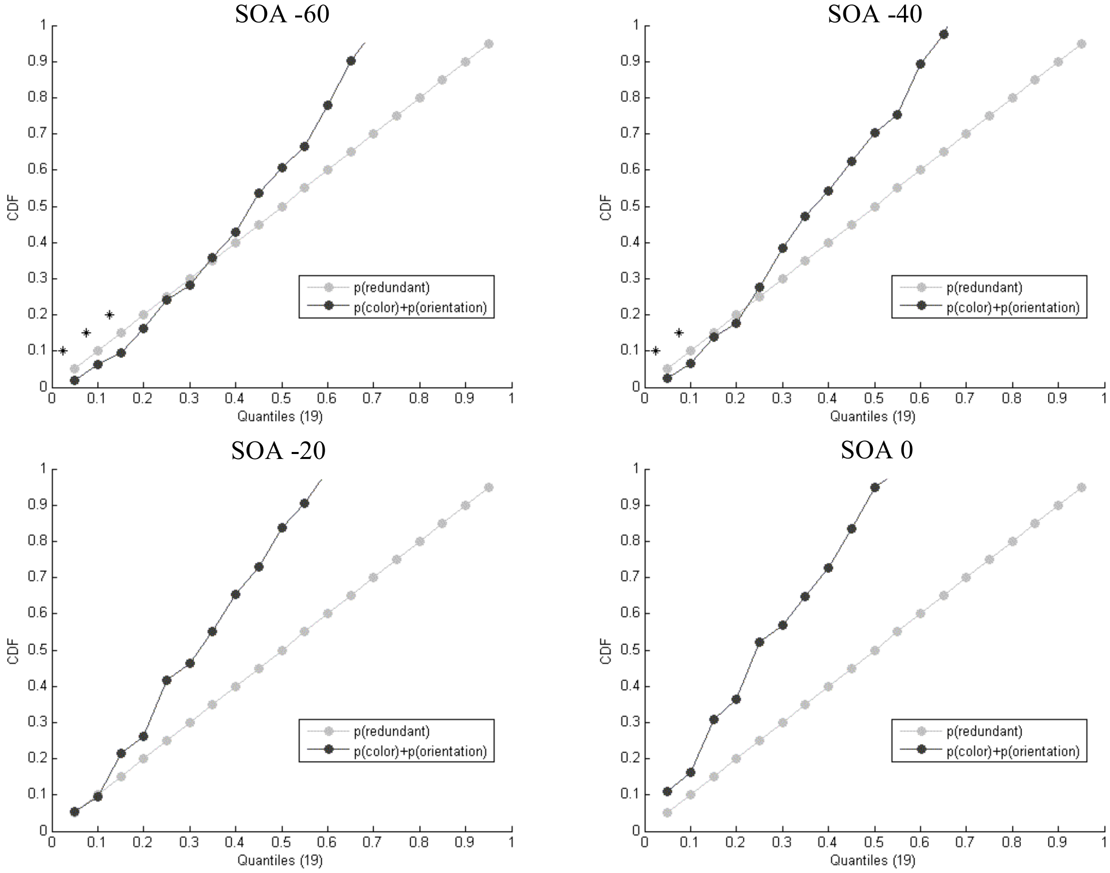


Figure 3.14. Results of the tests for violations of Miller's (1986) RMI in RTs according to the SOA in Experiment 1d. The dark grey curve represents the cumulative probability function for the summed probabilities of RTs to single targets having occurred at a given time t; the light grey curve represents corresponding redundant target probabilities. Significant violations are marked with a star ($p < .05$). Note that for the RMI to be satisfied, summed single dimension probabilities must be no smaller than redundant target probabilities.

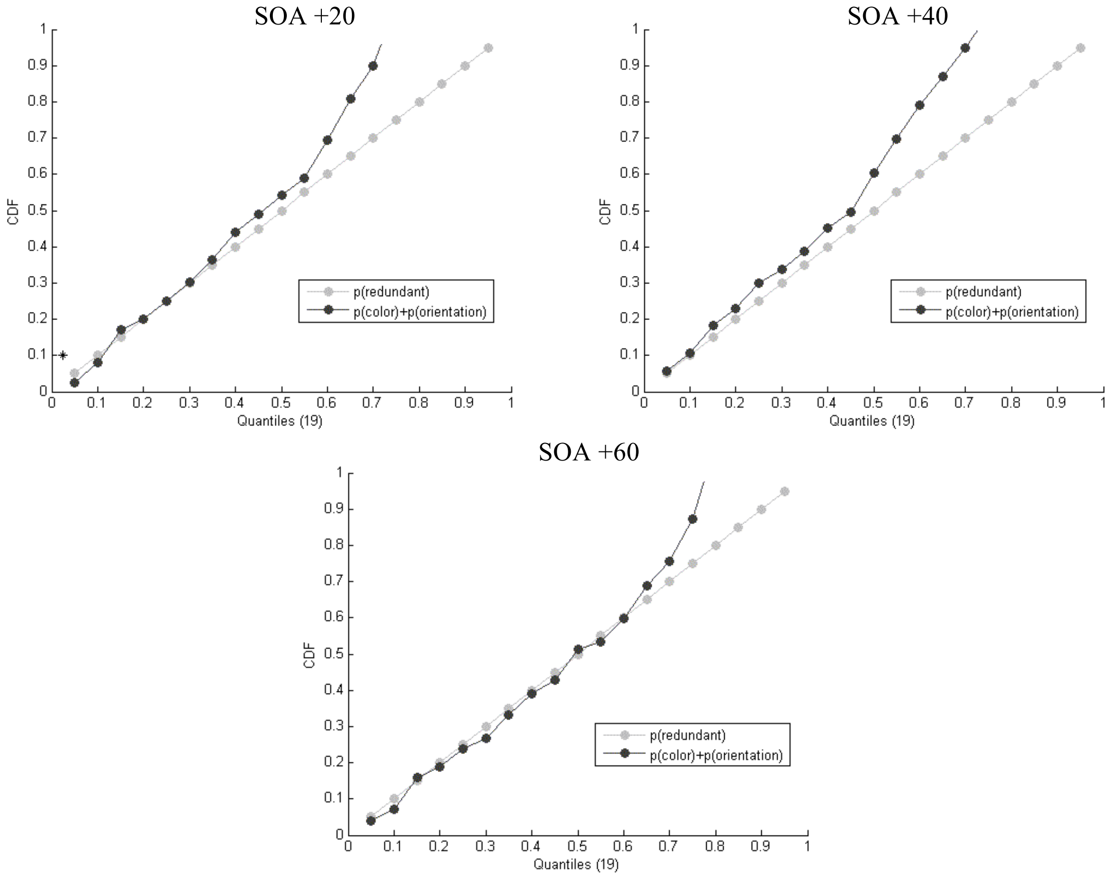


Figure 3.14 (Continued).

Altogether, all indicators converge to reveal a single optimal integration point. Although a maximal number of RMI violations were observed when color changed 40 to 60 ms before orientation, mean reaction times, redundancy gains and physiological chronometry analyses indicate that, as in the color-orientation condition, color and orientation were integrated best when orientation changed 20 ms before color. Furthermore, one RMI violation was observed at SOA 20 ms. According to the findings of Experiment 1c, this result suggests that, when color and orientation signals are integrated, color is processed faster than orientation, independently of the kinetic (static or dynamic) aspects of the display. However, adding an irrelevant feature (motion) to the display generates a general reaction time decrease (see below).

3.8. Task comparison and discussion

The present findings on feature change detection revealed that the optimal temporal feature integration does not necessarily occur when features change simultaneously; this finding contradicts the predictions of a mathematical model by Ulrich and Miller (1997). In Experiments 1a to 1d four indicators (mean reaction times, redundancy gains, mental chronometry and Race Model Inequality) revealed that motion and color signals were integrated best when motion changes 20 to 40 ms before color (Experiment 1a), motion and orientation when both features changes synchronously (Experiment 1b), and color and orientation when orientation changes 20 ms before color, and this, independently of whether all the displayed elements moved or not (Experiments 1c and 1d). Color signals seem thus to be processed around 20 ms before orientation and motion signals both of which are require the same processing time. Furthermore, in contradiction with previous studies claiming that not all visual features are integrated on a parallel coactive processing architecture (Koene & Li, 2007; Poom, 2009), RMI violations were observed in each paradigm for some SOAs. These findings contradict the V1 hypothesis (Li, 2002) that argues that RMI violations cannot be found in motion-color conditions because of a lack of cells in V1 tuned to this particular feature combination. Rather, the finding provides further evidence for the interpretation suggested by Krummenacher et al. (2001) who do not assume any dimensional restrictions to the integration of dimensional signals.

Further, the present results do not necessarily support the common form of contrast summation models (e.g., Cave & Wolfe, 1990; Koch & Ullmann, 1985; Wolfe, 1994). As mentioned above, saliency summation models implicitly assume that the processing of visual features occurs simultaneously. If it is assumed that the generation of contrast signals in feature-specific maps (which is temporally correlated to feature processing) is continuously transmitted to the master map level, two features with the same processing speed will generate an approximately comparable amount of contrast activation at each point in processing time (see the left panel of Figure 3.15), whereas features with asynchronous processing speed will produced unbalanced contrast signal, the fastest processed feature generating a higher amount of contrast activation than the slowest one during the same time interval. When summed at the master map level, the contrast signals of asynchronously processed features generate a smaller overall contrast signal than in the case of features with the same processing speed (see the central panel of Figure 3.15). This difference in the development of the contrast signal at the master map level permits targets defined by features with the same processing speed to generate a contrast peak that reaches the detection threshold faster. However, allowing the slowest process to start before the fastest process leads to counterbalancing processing time differences and allows for a faster activation accumulation that reaches the detection threshold on average faster than when both features begin their processing simultaneously (see the right panel of Figure 3.15).

A model integrating a temporal aspect as the feature processing speed can also provide an explanation for the lack of RMI violations for some specific feature combinations observed in previous studies (Koene & Li, 2007; Poom, 2009). As demonstrated by the results of Experiment 1, favoring the slowest processed feature by delaying the fastest feature yields RMI violations. Time seems thus to play a crucial role the mechanism governing feature integration.

Static versus moving items

A second important aspect of Experiment 1 is the performance difference between static and moving displays. As shown in Figure 3.16, introducing the task-irrelevant motion signal in the color-orientation condition slowed RTs. Because the different conditions did not all involve the same feature changes, only mean RTs of each condition were compared. A one-way ANOVA with the factor condition (static, moving) revealed a significant difference between conditions ($F(3,38) = 12.10$, $MS_e = 788.79$, $p < .001$). Multiple comparisons showed that mean RTs in static color-orientation trials ($M = 308.5$ ms, $SD = 35.8$ ms) were significantly faster than in motion-color trials ($M = 349.6$ ms, $SD = 28.1$ ms; $t(20) = -2.95$, $p < .01$) and in dynamic color-orientation trials ($M = 378.4$ ms, $SD = 16.1$ ms; $t(15.83) = -6.67$, $p < .001$). RTs in motion-orientation trials ($M = 329.8$ ms, $SD = 26.7$ ms) were significantly faster that in dynamic color-orientation trials ($t(18) = 4.93$, $p < .01$), whereas RTs in motion-color trials were significantly slower than in static color-orientation trials ($t(20) = -2.95$, $p < .01$). Finally, responses were significantly slower in dynamic color-orientation trials than in static color-orientation ($t(15.83) = -6.67$, $p < .001$) and in motion-orientation trials ($t(18) = 4.93$, $p < .01$).

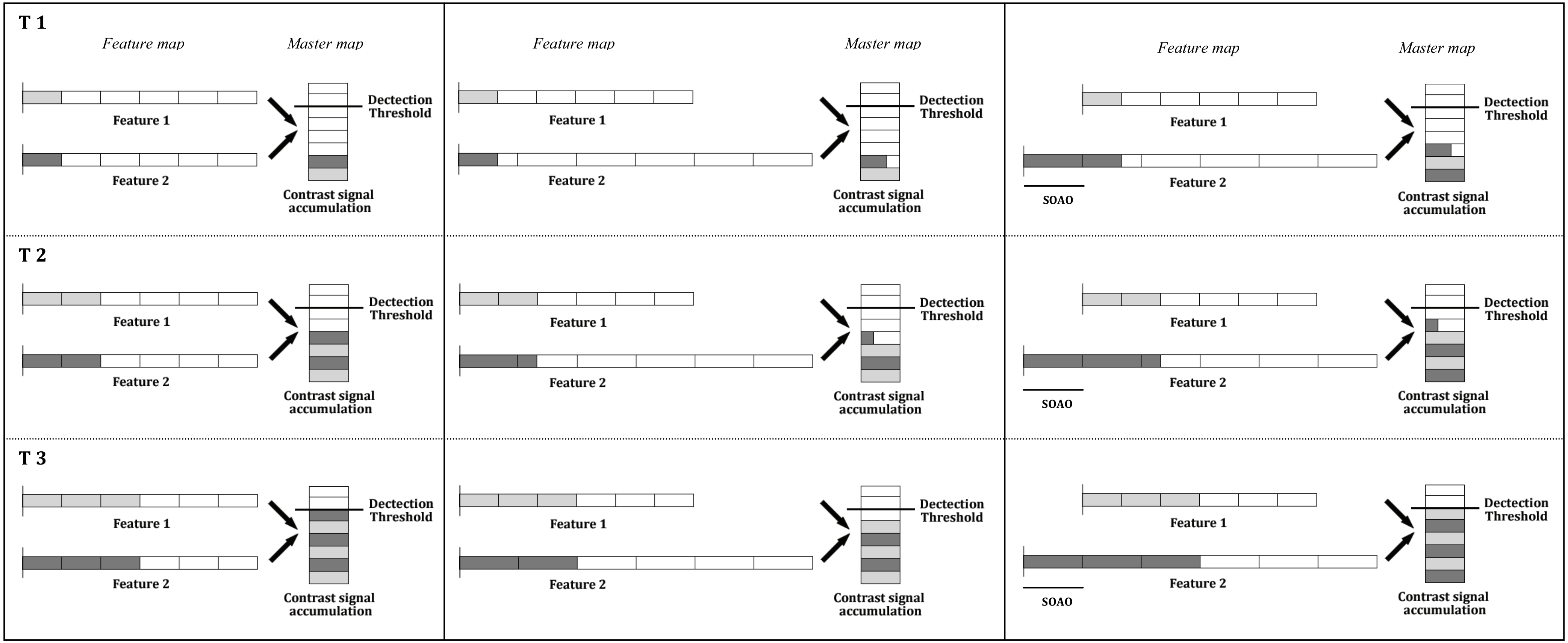


Figure 3.15. Schematic representation of a contrasts-maps summation model taking account of the feature–based contrast generation speed. The length of the segmented bars corresponds to the processing speed of the feature. The processing progression is symbolized by the filling up of the segmented bars (in light and dark grey). The column at the right side corresponds to the summation of the contrasts signal at the master map level. Each row of the figure indicates the processing progression at three arbitrary chosen times. The **left panel** represents the signal contrast progression for features with the same processing speed, whereas the two other panels represent. The **central panel** displays the signal progression for features with asynchronous processing speed for a simultaneous feature change, and the **right panel** for an asynchronous feature change.

These comparisons show that detecting a color-orientation defined target in a moving display was more difficult than in a static display, and conditions involving motion as a target feature were at an intermediate location. Tough statistically similar, conditions involving motion as target feature reveal diverging preferences. RTs of motion-orientation trials were closer to RTs of in static color-orientation trials, whereas RTs of motion-color trials were closer to RTs observed in dynamic color-orientation trials (see Figure 3.16).

Supplementary evidence of the influence of display dynamics was unveiled by comparing RTs for a singly defined target of the different conditions (see Table 3.6). A one factor ANOVA (with the factor condition: motion-color, color-orientation and moving color-orientation paradigms) of RTs for targets defined uniquely by color revealed a significant difference between conditions ($F(2,29) = 12.34$, $MS_e = 947.42$, $p < .001$). Multiple comparisons indicated that the detection of a color-defined target was significantly faster in the static color-orientation than in the motion-color condition ($t(20) = 2.74$, $p < .05$) and the dynamic color-orientation condition ($t(14.72) = -5.02$, $p < .001$). Although a color target was detected 22.2 ms faster in the motion-color condition than in the dynamic color-orientation condition, this difference not statistically significant ($t(18) = -2.18$, $p > .10$).

Table 3.6

Mean RTs in ms (and standard deviation) for color and orientation singly defined targets through paradigms.

Paradigm	Color		Orientation	
Static color-orientation	323.93	(28.07)	303.91	(35.38)
With motion	365.66	(40.63)	333.25	(27.25)
Dynamic color-orientation	387.84	(15.71)	375.81	(25.41)

Similar results were observed for targets defined exclusively by orientation. A one factor ANOVA (with the factor condition: motion-orientation, color-orientation and dynamic color-orientation paradigms) showed that conditions differed significantly from each other ($F(2,29) = 15.61$, $MS_e = 905.44$, $p < .001$). Multiple comparisons showed that targets defined by orientation were detected significantly slower in dynamic color-orientation trials than in motion-orientation ($t(18) = -3.61$, $p < .05$) and in static color-orientation trials ($t(20) = -5.37$, p

< .001). Furthermore, though there was a difference of 29.4 ms between RTs for orientation targets in color-orientation and static color-orientation conditions, the difference was not significant either (*t*(20) = 2.14, *p* = .091).

Altogether, the present results suggest that visual features are not processed fully independently of each other. The fact that RTs for targets defined either by color or orientation with motion as a task-irrelevant feature speaks in favor of the existence of inter-channel crosstalk. If motion produced only a general RT increase, color- and orientation-defined targets should have generated similar RTs in paradigms where motion was either task-relevant (Experiments 1a and b) or task-irrelevant (Experiment 1d). However, reaction times for these targets increased in the last experiment, suggesting that a task-irrelevant motion signal influences the processing of color and orientation signals. Features do not seem to be completely impermeable to each others.

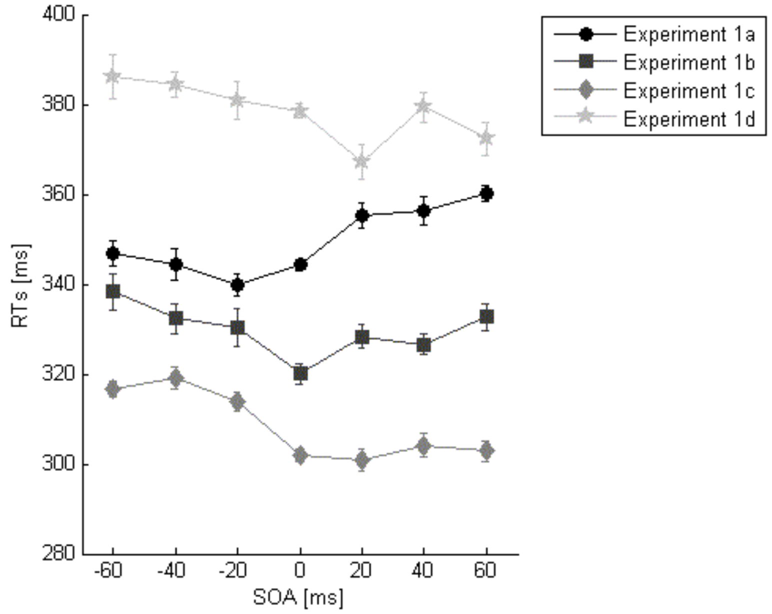


Figure 3.16. Detection task comparisons. The upper line (stars) stands for mean RTs (and standard error) for redundant trials for each SOA in Experiment 1d (dynamic color-orientation paradigm). The second line (circles) represents the results of Experiment 1a (motion-color paradigm) and the third line (squares) the results of the Experiment 1b (motion-orientation paradigm), while the lower line (diamonds) represents the results of Experiment 1c (static color-orientation paradigm). A negative SOA indicates the time interval between the change of the first feature (indicated in the paradigm name) and the other feature change, whereas a positive SOA means an opposite feature changes order.

3.9. Experiment 2a: Motion - color conjunction task

Experiment 1 showed that features of a redundantly defined target seem not to have the same processing speed. However, a target object is not always as easily detectable as in the previous tasks. It has been demonstrated that reaction times increase when the target differs from distractors by a particular feature conjunction (e.g., Treisman & Gelade, 1980). A red horizontal bar can be faster detected among green vertical bars (pop-out search) than among red or green vertical and green horizontal bars (conjunction search). Contrary to a pop-out task, performing a conjunction task requires deeper processing of feature, namely not only the detection of a feature (contrast signal), but also the identification of the feature value.

However, in a conjunction task, relative temporal contributions of the features constituting the target are difficult to gauge in the traditional experimental procedure in which all the search items are displayed simultaneously. For this reason, Schönwälder (2006) used an asynchronous feature change paradigm in which the target identity had to be reported. A target defined on multiple dimensions, surrounded by homogenous distractors (as in the detection tasks of the present study), was displayed in each trial and participants had to respond only if the target was characterized by specific predefined feature combination. Schönwälder, not surprisingly, found that the time needed to identify features in a global motion-color conjunction was higher than the mere detection of the presence of a target; further, RTs increased inversely to the time interval between the two feature changes; the longest reaction times were observed when both features changed simultaneously.

Experiment 2 is aimed at extending the understanding of temporal integration of a set of visual features in a conjunction search task. The three pairs of features used in the detection tasks of Experiment 1 (a to d) were investigated under conjunction task conditions. As in Schönwälder's (2006) conjunction task, only targets differing from distractors on multiple dimensions were displayed and participants were instructed to respond only to two particular predefined feature change combinations. As in the classical conjunction search task, this variation of the paradigm needs feature identification. Note that this task is also is closer to Moutoussis and Zeki's (1997a, b) task that required a conscious feature pairing. Experiment 2a investigated the temporal integration of motion and color in a conjunction task.

3.9.1. Method

Participants. Ten observers (eight female and two male) took part in Experiment 2a. All were students at the University of Fribourg. They were paid 10Fr CH. They were aged between 25 and 38 year old (median = 27.5). Observers had a normal or a corrected to normal vision, including normal vision color.

Design. All trials contained targets differing from distractors on two dimensions (color and motion). The first change occurred after a delay of 800 to 1200 ms (five steps separated by 100 ms) and was followed by the second change after an SOA of between -100 ms to 100 ms (11 equal steps). Out of the four possible change combinations (color: red or blue, motion: 62.25° diagonal left or right motion direction), each observer was assigned two complementary pairs (red target and left diagonal motion; blue target and right diagonal motion *or* red target and right diagonal motion; blue target and left diagonal motion). Observers were instructed to respond as quickly as possible to the predefined targets (go trials) and to avoid making errors. The two other feature combinations had to be ignored (no-go trials). RT was measured from the onset of the second feature change.

Procedure. In a first step, a short session with a detection task of singly defined targets (color and motion) was conducted (designed as the above mentioned detection tasks). Participants had to complete a warm-up block of 9 trials, 6 go trials (3 color and 3 motion conditions) and 3 no-go (with instructions at the beginning and feedbacks displayed on the screen) and a block of 75 trials composed by 25 trials per go condition and 25 for the no-go condition where reaction times were measured. This condition served as a baseline condition.

The conjunction task session was run in a second step. The observers performed a “warm-up” block of 12 trials which was followed by 15 experimental blocks of 44 trials. The whole experiment took about 50 minutes to complete. As in the detection task, instructions were presented orally by the investigator and displayed on the screen at the beginning of the warm-up block and the experience. The warm-up block contained 12 trials, 6 go and 6 no-go. All the four different combinations were displayed with one of the three warm-up SOAs (-200, 0, 200 ms)[2]; the comparably high SOAs values were chosen to make observers aware that a time interval between feature changes could occur. After each trial, a feedback about the

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[2] Larger SOAs for redundant targets were used in the warm-up block (than in the experimental blocks) to stress the possible time interval between feature changes.

correctness of participant's response was also presented on the screen, but the responses were not recorded. Each experimental block was composed by 22 go and 22 no-go redundant trials with 11 possible SOAs from -100 to 100 ms. At the beginning of each block a screen indicated the next block number and the participant had to depress the space bar start the block. A total of 660 recorded trials were presented in randomized order.

Stimuli, apparatus and setting were the same as in the detection tasks of Experiment 1 described above.

3.9.2. Results

Anticipatory and extremely slow responses, as well as extreme reaction times were excluded from analysis. Misses and false alarms corresponded to less than 10% of the trials. Given that RTs for the single targets (detection task) were faster than those for two-dimensional conjunction targets, differences between single (detection) and two-dimensional targets were not analyzed.

Table 3.7

Mean correct RTs (with standard deviation) and error rates for missed targets, false alarms and extreme RTs for target types in Experiment 2a.

				Error rates (%)					
Target type		RT (ms)		Miss		False alarm		Extremes	
Single defined targets									
Motion		373.50	(30.79)	0.00	(0)	0.40	(1.27)	1.60	(2.80)
Color		380.31	(32.01)	0.00	(0)			1.20	(1.93)
Redundant defined targets									
FCA	-100ms	587.10	(97.66)	1.67	(4.23)	3.33	(4.16)	2.00	(2.33)
	-80ms	600.44	(93.55)	0.33	(1.05)	5.33	(5.71)	2.00	(2.33)
	-60ms	608.37	(83.14)	0.00	(0.00)	4.00	(3.06)	2.33	(2.25)
	-40ms	633.34	(81.30)	1.00	(3.16)	2.33	(4.17)	2.33	(2.25)
	-20ms	659.09	(87.70)	0.33	(1.05)	3.33	(3.14)	1.00	(1.61)
	0ms	661.91	(80.65)	0.67	(1.41)	3.33	(3.85)	1.67	(1.76)
	20ms	642.69	(81.96)	0.67	(2.11)	5.00	(3.24)	2.33	(2.25)
	40ms	648.28	(99.64)	1.33	(3.22)	3.33	(2.72)	2.33	(1.61)
	60ms	635.52	(84.63)	1.33	(3.22)	3.67	(3.99)	2.00	(2.33)
	80ms	620.95	(69.40)	1.67	(5.27)	4.00	(5.16)	1.67	(1.76)
	100ms	628.38	(82.16)	2.00	(5.26)	5.00	(5.27)	1.67	(2.36)
	Mean	629.64	(82.94)	1.00	(2.54)	3.88	(0.91)	1.94	(0.80)

A one way ANOVA (with the factor SOA) of the error rates showed no significant difference between miss (*F*(1.45,13.06) = 1.01, MS_e = 28.78, *p* > .05; Huynh-Feldt-corrected degrees of freedom) and false alarm rates (*F*(6.27,56.41) = .85, MS_e = 15.61, *p* > .05; Huynh-Feldt-corrected degrees of freedom) of the different SOAs.

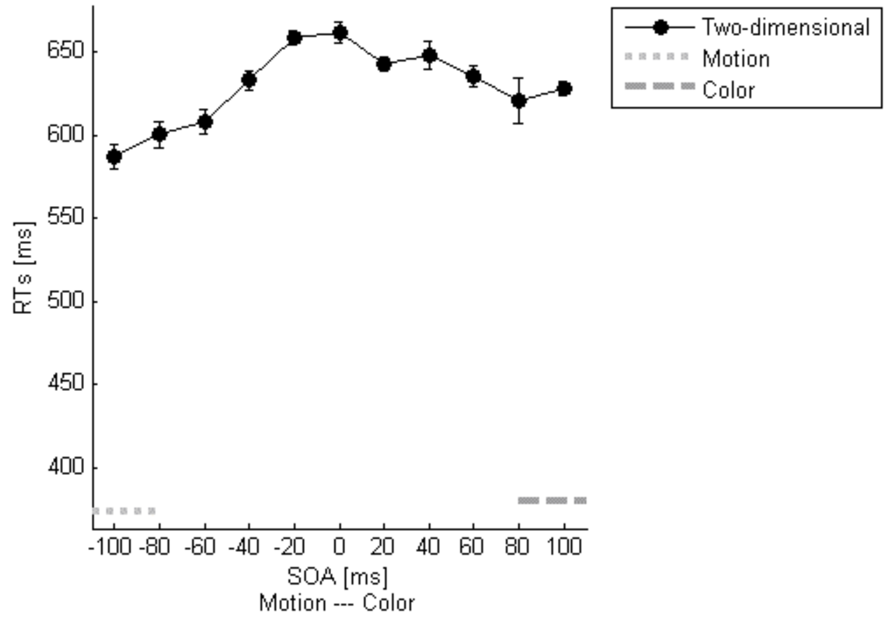

Figure 3.17. Mean RTs for the singly defined targets and for two-dimensionally defined targets as a function of the SOA in Experiment 2. The solid line represents the mean RT (and standard error) for the two-dimensional targets for each SOA. A negative SOA indicates that motion changed first, whereas a positive SOA signifies that color changed first. Dashed lines at each side of the figure indicate respectively the mean RT for the motion and color targets.

The mean RTs and the different error rates are presented in Table 3.7 and shown in Figure 3.17. A one-way repeated measures ANOVA (with the factor SOA: SOA from -100 to +100) showed a significant difference between single and two-dimensional trials (*F*(1.02,9.16) = 129.56, MS_e = 3229.58, *p* < .001; Huynh-Feldt-corrected degrees of freedom); multiple comparisons indicated that the motion targets (*M* = 373.5 ms, *SD* = 30.8 ms) are significantly faster detected than color targets (*M* = 380.3 ms, *SD* = 32 ms; *t*(9) = 3.08, *p* < .05), both significantly faster processed than two-dimensional targets (great mean = 629.6 ms, *SD* = 82.9 ms; respectively *t*(9) = 11.37, *p* < .001, and *t*(9) = 11.45, *p* < .001). [A conjunction task seems thus to produce redundancy *costs* rather than redundancy gains.] As in Schönwälder's (2006) study, the largest conjunction search cost was observed when features changed simultaneously (see Table 3.7). Moreover, the *inverted* V-curve for the two-dimensional trials is also supported by a significant main effect of SOA ($F(8.08,72.70) = 9.92$, $MS_e = 707.55$, $p < .001$) and a quadratic effect ($F(1,9) = 75.24$, $MS_e = 452.07$, $p < .001$), a linear trend was also observed ($F(1,9) = 17.52$, $MS_e = 762.71$, $p < .01$). Multiple comparisons did not indicate significant differences between adjacent SOAs (all $p > .10$).

3.10. Experiment 2b: Motion - orientation conjunction task

3.10.1. Method

Participants. Ten observers (six female and four male) took part to this experience. All were students at the University of Fribourg. They were paid 10Fr CH. They were aged between 25 and 38 year old (median = 27.5). Observers had a normal or a correct-to-normal vision, including normal vision color, except for one. In this case, the color-blindness of the experimenter does not play any role because of the fact that all elements are green and remain green during the whole experiment.

Design. In this task all trials contained a target differing from distractors on two dimensions (orientation and motion). The first change occurred after a delay of 800 to 1200 ms (five steps separated by 100 ms) and was followed by the second change after a SOA of between -100 ms to 100 ms (11 equal steps). Out of the four possible change combinations (orientation: left or right, motion: 62.25° diagonal left or right motion direction), each observer was assigned two complementary pairs (left target and left diagonal motion; right target and right diagonal motion *or* left target and right diagonal motion; right target and left diagonal motion). Observers were instructed to respond as quickly as possible to the two predefined targets (go trials) and also to avoid making errors. The two other feature combinations had to be ignored (no-go trials). RT was measured from the onset of the second feature change.

Procedure, stimuli, apparatus and setting are the same as in the detection tasks of Experiment 1 described above.

Table 3.8

Mean correct RTs (with standard deviation) and error rates for missed targets, false alarms and extreme RTs for target types in conjunction task Experiment 2b.

				Error rates (%)					
Target type		RT (ms)		Miss		False alarm		Extremes	
Single defined targets									
Motion		355.47	(32.63)	0.00	(0.00)	0.80	(1.69)	1.20	(1.93)
Color		348.60	(29.30)	0.00	(0.00)			2.40	(2.07)
Redundant defined targets									
FCA	-100ms	492.30	(35.33)	0.00	(0.00)	2.00	(2.33)	2.00	(1.72)
	-80ms	493.20	(48.36)	0.00	(0.00)	4.33	(4.17)	1.33	(1.72)
	-60ms	497.93	(55.52)	0.00	(0.00)	4.67	(4.22)	2.00	(1.72)
	-40ms	506.48	(50.61)	0.00	(0.00)	3.00	(3.99)	3.00	(1.89)
	-20ms	518.75	(43.28)	0.00	(0.00)	3.67	(3.32)	2.00	(1.72)
	0ms	528.33	(50.87)	0.00	(0.00)	3.33	(3.85)	2.67	(2.63)
	20ms	522.48	(53.05)	0.00	(0.00)	2.00	(2.81)	2.00	(1.72)
	40ms	491.32	(51.53)	0.00	(0.00)	3.67	(4.29)	2.00	(1.72)
	60ms	490.10	(49.26)	0.00	(0.00)	3.67	(2.46)	2.33	(1.61)
	80ms	482.28	(38.45)	0.00	(0.00)	5.33	(4.77)	2.33	(2.25)
	100ms	476.09	(51.45)	0.67	(1.41)	9.67	(7.28)	1.00	(1.61)
	Mean	499.93	(46.48)	0.06	(0.13)	4.12	(2.62)	2.06	(0.47)

3.10.2. Results

The RT exclusion criteria as in the previous experiments were applied. A repeated measures ANOVA (with the factor SOA) of miss rates did not show a significant difference between SOAs ($F(1,9) = 1.00$, MS$_e$ = 1.00, $p > .05$; Huynh-Feldt-corrected degrees of freedom); however, false alarm rates showed a significant main effect of SOA ($F(7.30,65.72) = 3.83$, MS$_e$ = 15.77, $p < .01$; Huynh-Feldt-corrected degrees of freedom) but multiple comparisons indicated no significant differences between SOAs (all $p > .10$).

The mean RTs are presented in Table 3.8 and shown in Figure 3.18. A one way repeated measures ANOVA with the factor target type showed that a significant difference between singly and redundantly defined trials ($F(2,18) = 155.02$, MS$_e$ = 471.12, $p < .001$); multiple comparisons indicated that motion ($M = 355.5$ ms, $SD = 32.6$ ms) and orientation targets ($M = 348.6$ ms, $SD = 29.3$ ms) were processed in the same time ($t(9) = 1.23$, $p > .10$), but were significantly faster than the two-dimensional targets (mean = 499.9 ms, $SD = 46.5$ ms; respectively, $t(9) = 11.91$, $p< .001$, and $t(9) = 14.83$, $p < .001$). As in the motion-color condition, RTs to two-dimensional targets were highest. The *inverted* V-curve for the two-dimensional targets was also substantiated by a repeated measures ANOVA of reaction times for two-dimensional targets at each SOA (mean effect of the SOA: $F(6.5,58.48) = 14.69$, $MS_e = 300.69$, $p < .001$ - Huynh-Feldt-corrected degrees of freedom; quadratic effect: $F(1,9) = 119.02$, $MS_e = 153.14$, $p < .001$), accompanied by a significant linear trend ($F(1,9) = 18.52$, $MS_e = 149.93$, $p < .01$); Moreover, multiple comparisons indicated a single significant difference between adjacent SOAs (i.e., between SOA 20 and 40; $t(9) = 5.00$, $p < .05$, $p > .10$ for all other; see Figure 3.18).

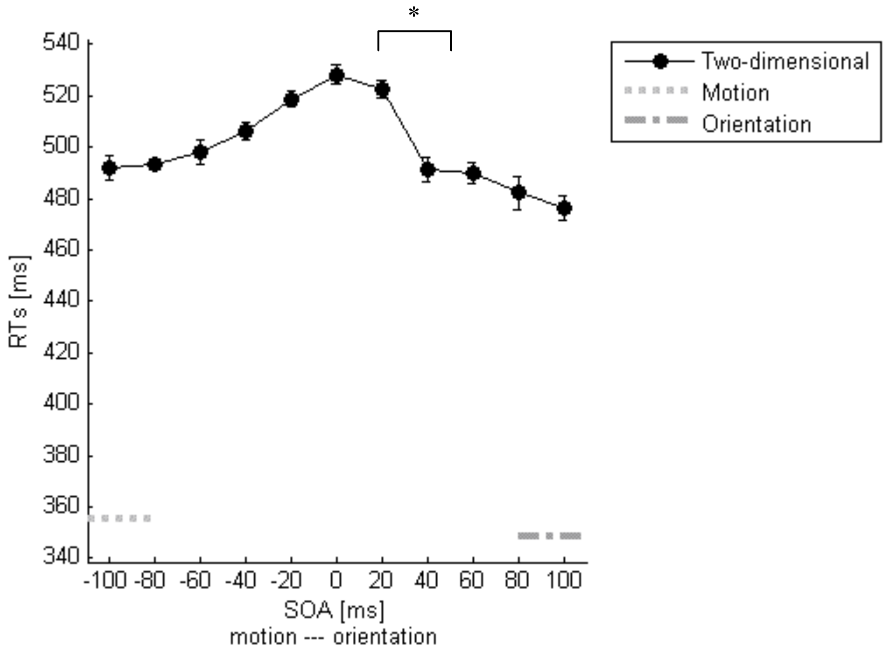

Figure 3.18. Mean RTs for singly and for redundantly defined targets according to the SOA in Experiment 2b. The solid line represents the mean RT (and standard error) for the two-dimensional targets for each SOA. A negative SOA indicates that motion changed first, whereas a positive SOA signifies that orientation changed first. Significant difference between adjacent SOAs is indicated by a star ($p < .05$). Dashed lines at each side of the figure indicate respectively the mean RT for the motion and orientation targets.

3.11. Experiment 2c: Color – orientation conjunction task

3.11.1. Method

Participants. Thirteen observers (four female and nine male) took part in Experiment 2c. All were students at the University of Fribourg. They were paid 10Fr CH. They were aged between 21 and 25 year old (median = 23). Observers had a normal or a correct-to-normal vision.

Design. In this task all trials contained targets differing from distractors on two dimensions (color and orientation). The first change occurred after a delay of 800 to 1200 ms (five steps separated by 100 ms) and was followed by the second change after a SOA of between -100 ms to 100 ms (11 equal steps). Out of the four possible change combinations (orientation: left or right, color: red or blue), each observer was assigned two complementary pairs (red left-tilted and blue right-tilted bar *or* red right-tilted and blue left-tilted bar). Observers were instructed to respond as quickly as possible to the predefined targets (go trials). Observers were also instructed to avoid making errors. The two other feature combinations had to be ignored (no-go trials). Reaction time was measured from the onset of the second feature change.

Procedure, stimuli, apparatus and setting are the same as in the detection tasks of Experiment 1 described above.

3.11.2. Results

The RTs exclusion criteria of the previous experiments were applied in Experiment 2c. One participant was excluded because of exceeding the error criterion of 10 percent. Error analysis (a one way ANOVA with the factor SOA) showed that there was no significant difference between misses for the different SOAs ($F(2.79,30.68) = 1.35$, $MS_e = 5.34$, $p > .10$; Huynh-Feldt-corrected degrees of freedom), no difference was also found for false alarm rates ($F(8.08,88.92) = 1.37$, $MS_e = 11.05$, $p > .10$; Huynh-Feldt-corrected degrees of freedom).

Table 3.9

Mean correct reaction times (with standard deviation) and error rates for missed targets, false alarms and extreme reaction times for target types in Experiment 2c.

				Error rates (%)					
Target type		RT (ms)		Miss		False alarms		Extremes	
Single defined targets									
Color		378.13	(67.06)	0.00	(0.00)	0.67	(1.56)	2.00	(2.09)
Orientation		360.98	(71.30)	0.00	(0.00)			3.00	(1.81)
Redundant defined targets									
	-100ms	529.64	(91.85)	1.11	(2.60)	1.11	(2.17)	1.67	(2.25)
	-80ms	526.09	(84.91)	0.28	(0.96)	2.50	(3.22)	1.94	(1.72)
	-60ms	545.82	(88.96)	0.28	(0.96)	3.06	(3.88)	1.67	(2.25)
	-40ms	553.47	(93.00)	0.28	(0.96)	2.78	(3.43)	1.67	(1.74)
	-20ms	557.84	(81.26)	1.11	(2.17)	1.67	(3.02)	2.22	(2.60)
FCA	0ms	564.98	(83.00)	0.83	(2.07)	2.50	(4.52)	2.22	(2.17)
	20ms	552.54	(90.21)	0.83	(2.07)	2.78	(3.98)	2.50	(1.51)
	40ms	536.41	(75.93)	0.00	(0.00)	2.22	(2.60)	2.22	(2.60)
	60ms	517.25	(65.05)	0.56	(1.30)	5.00	(3.89)	1.94	(1.72)
	80ms	514.88	(66.15)	0.00	(0.00)	3.61	(4.37)	1.94	(2.23)
	100ms	515.31	(57.20)	0.28	(0.96)	2.50	(2.51)	2.78	(1.93)
	Mean	537.66	(77.46)	0.51	(0.98)	2.70	(2.03)	2.45	(1.08)

The mean reaction times and error rates are presented in Table 3.9 and shown in Figure 3.19. A one-way repeated measures ANOVA (with the factor target type) showed a significant difference between singly and redundantly defined trials ($F(1.02,12.21) = 36.67$, MS_e = 6098.81, $p < .001$; Huynh-Feldt-corrected degrees of freedom); multiple comparisons indicated that the orientation targets (M = 361 ms, SD = 71.3 ms) were significantly faster processed than the color targets (M = 378.1 ms, SD = 67.1 ms; $t(11) = 4.78$, $p < .01$). Color targets were faster detected than two-dimension targets (great mean = 537.6 ms, SD = 77.5 ms; respectively $t(11) = 6.12$, $p < .001$, and $t(11) = 6.00$, $p < .001$). As in the other conjunction tasks, simultaneous two-dimensional trials had the highest reaction times. The *inverted* V- curve for the two-dimensiona*l* trials was also substantiated in a one-way repeated measures ANOVA of RTs for two-dimensional targets at each SOA (mean effect of the SOA: $F(6.12) = 7.27$, MS_e = 897.47, $p < .001$ and quadratic effect: $F(1,11) = 35.28$, MS_e = 696.63, $p < .001$). Multiple comparisons did not reveal significant differences between adjacent SOAs (all $p < .10$).

3.12. Experiment 2d: Moving color-orientation conjunction task

3.12.1. Method

Participants. The same ten female observers as in the moving color-orientation detection task took part in Experiment 2d. All were students at the University of Fribourg. They were paid 10Fr CH and were aged between 21 and 25 year old (median = 22). All observers had a normal or a correct-to-normal vision, including normal vision color.

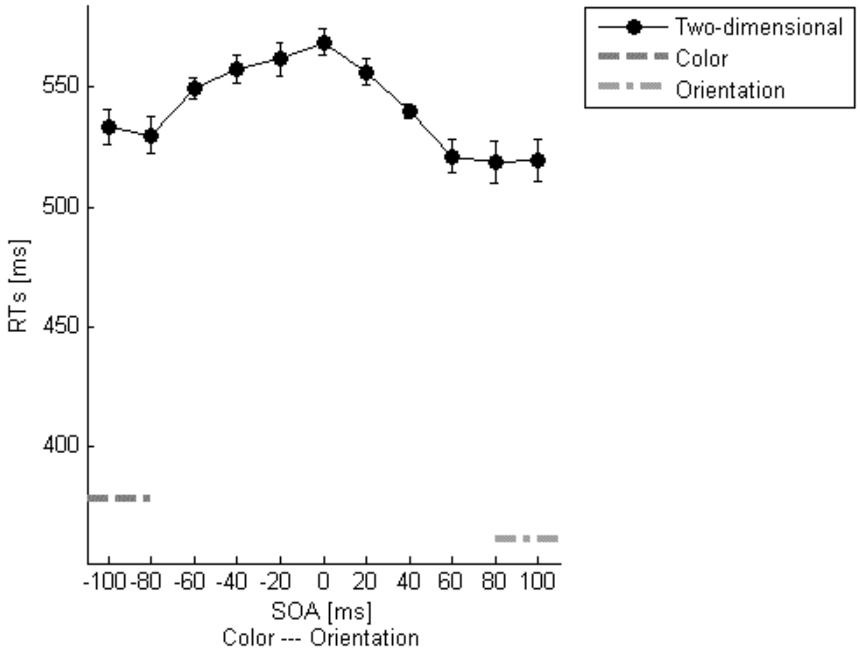

Figure 3.19. Mean RTs for the singly defined targets and for two-dimensionally defined targets as a function of the SOA in Experiment 2c. The solid line represents the mean RT (and standard error) for the two-dimensional targets for each SOA. A negative SOA indicates that motion changed first, whereas a positive SOA signifies that orientation changed first. Dashed lines at each side of the figure indicate respectively the mean RT for the color and orientation targets.

Design, timing, apparatus, setting and procedure were identical to the color and orientation conjunction task.

Stimuli. Stimuli were identical to those used in the color-orientation conjunction task. The unique difference laid in the fact that all stimuli on the display adopted the same sinusoidal horizontal motion used in paradigms involving motion (according to a sinusoidal function with a maximal amplitude of 1.15° of visual angle and an increase of α by 7° per frame).

3.12.2. Results

The RT exclusion criteria used in previous experiences were applied. One participant was excluded from the analysis because of exceeding the criterion of 10% errors. A one-way repeated mesures ANOVA (with the factor SOA) showed no significant difference between miss (*F*(3.57,32.12) = .748, MS_e = 7.72, *p* > .10; Huynh-Feldt-corrected degrees of freedom) and false alarms rates (*F*(8.57,77.13) = 1.38, MS_e = 14.49, *p* > .10; Huynh-Feldt-corrected degrees of freedom) for the different SOAs.

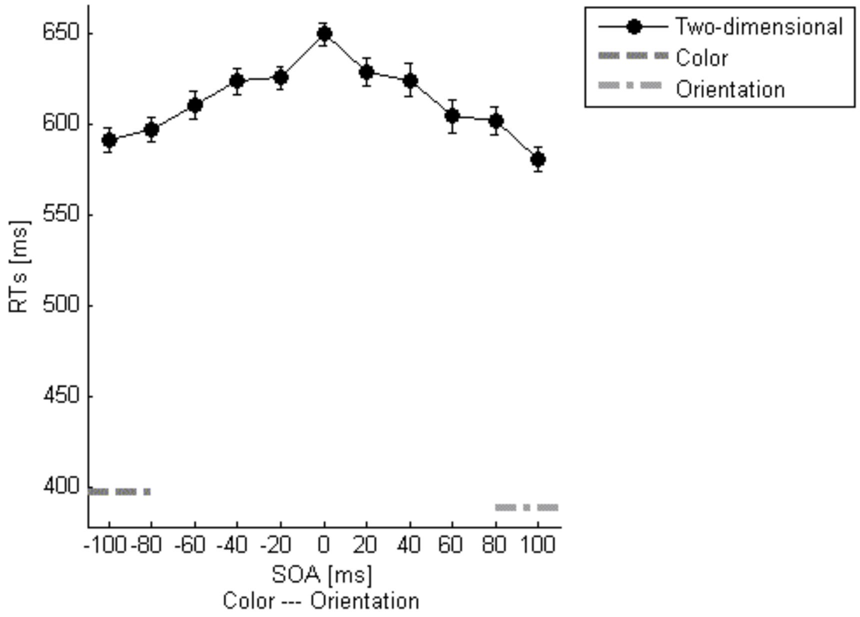

Figure 3.20. Mean RTs for the singly defined targets and for two-dimensionally defined targets as a function of the SOA in Experiment 2d. The solid line represents the RT (and standard error) for the two-dimensional targets for each SOA. A negative SOA indicates that motion changed first, whereas a positive SOA signifies that orientation changed first. Dashed lines at each side of the figure indicate respectively the mean RT for the color and orientation targets.

The mean RTs and different error rates are presented in Table 3.10 and shown in Figure 3.20. A one way-repeated measures ANOVA (with target type as factor) showed a significant difference between target type (*F*(1.17,10.49) = 113.14, MS_e = 2438.72, *p* < .001; Huynh-Feldt-corrected degrees of freedom); Multiple comparisons indicated that orientation (*M* = 388.7 ms, *SD* = 50 ms) and color targets (*M* = 397.9 ms, *SD* = 33.9 ms; *t*(9) = -1.40, *p* > .10) were processed at the same speed, and faster detected than two-dimensional trials (great mean = 612.8 ms, *SD* = 60.7 ms; respectively *t*(9) = 11.66, *p* < .001, and *t*(9) = 10.34, *p* < .001). As in the other conjunction tasks simultaneous two-dimensional trials had the RTs. The *inverted* V-curve for the two-dimensional trials was observed (mean effect of the SOA: $F(8.09,72.79) = 6.7$, $MS_e = 732.82$, $p < .001$, and quadratic effect: $F(1,9) = 46.83$, $MS_e = 730.62$, $p < .001$). Multiple comparisons did not indicate significant differences between adjacent SOAs (all $p > .10$).

Table 3.10

Mean correct RTs (with standard deviation) and error rates for missed targets, false alarms and extreme RTs for target types of conjunction task in moving color-orientation paradigm of Experiment 2.

				Error rates (%)					
Target type		RT (ms)		Miss		False alarms		Extremes	
Single defined targets									
Color		397.93	(33.94)	0.00	(0.00)	0.40	(1.30)	0.80	(1.69)
Orientation		388.71	(50.04)	0.00	(0.00)			2.40	(2.80)
Redundant defined targets									
FCA	-100ms	591.81	(67.25)	1.00	(1.61)	3.33	(4.16)	3.33	(2.72)
	-80ms	597.13	(51.13)	1.33	(2.33)	4.00	(4.66)	3.00	(1.89)
	-60ms	610.61	(49.92)	1.67	(4.23)	2.00	(3.22)	1.33	(1.72)
	-40ms	624.18	(65.81)	0.67	(1.41)	5.33	(5.49)	2.67	(2.11)
	-20ms	625.76	(51.57)	1.67	(2.83)	4.67	(3.91)	2.00	(1.72)
	0ms	650.03	(58.14)	1.67	(3.24)	1.00	(1.61)	2.33	(2.25)
	20ms	628.76	(74.03)	1.67	(2.36)	2.00	(3.58)	3.33	(1.57)
	40ms	624.51	(80.78)	0.33	(1.05)	3.00	(3.67)	2.33	(2.25)
	60ms	604.64	(77.02)	1.67	(3.24)	4.00	(4.10)	3.33	(2.22)
	80ms	602.25	(68.75)	1.00	(1.61)	4.00	(5.40)	2.33	(2.74)
	100ms	580.78	(61.71)	1.00	(2.25)	4.33	(5.22)	2.67	(2.11)
	Mean	612.77	(60.71)	1.24	(1.96)	3.14	(2.36)	2.85	(1.21)

3.13. Task comparison and discussion

Each of the conjunction task conditions of Experiment 2 showed the longest RT to be systematically associated with simultaneous feature changes and in all conditions an inverted V-shape curve as a function of the SOA (see Figure 3.21) was found (as also reported by Schönwälder, 2006, in a task with objects moving across the entire screen rather than within a small place as in Experiment 2). Target identification time depended strongly on the condition. A one factor ANOVA with the paradigms as factor showed that the condition significantly affected the RT grand means (*F*(3,38) = 7.61, MS_e = 5212.28, *p* < .001). Multiple comparisons revealed that RT grand means for the motion-orientation condition (*M* = 499.9 ms, *SD* = 46.5 ms) was significantly lower than for the motion-color condition (*M* = 629.6 ms, *SD* = 82.9 ms; *t*(18) = 4.31, *p* < .01) and the dynamic color-orientation condition (*M* = 612.8 ms, *SD* = 60.7 ms; *t*(18) = 4.67, *p* < .01). Targets in static the color-orientation condition (*M* = 537.7 ms, *SD* = 77.5 ms) were on average identified significantly faster than in the motion-color condition (*t*(20) = 2.69, *p* < .05), whereas targets defined by motion and color were identified significantly more slowly than targets in static color-orientation (*t*(20) = 2.69, *p* < .05) and motion-orientation conditions (*t*(18) = 4.31, *p* < .01).

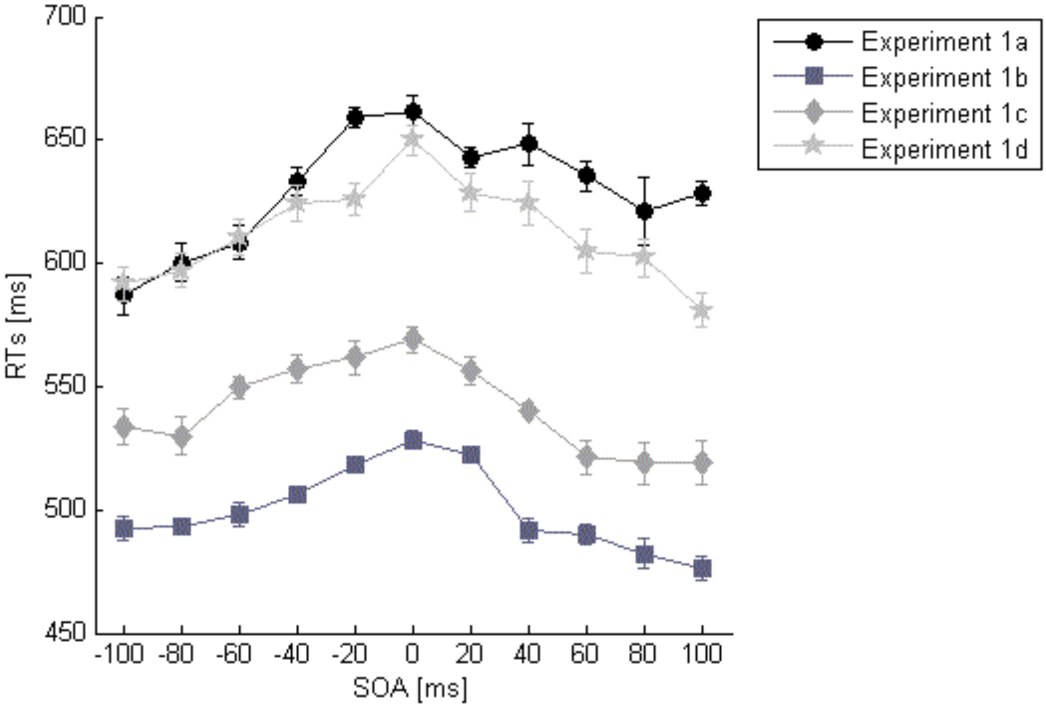

Figure 3.21. Comparison of the conjunction tasks in Experiment 2. The upper line (circles) stands for mean RTs (and standard error) for two-dimensional trials for each SOA in Experiment2a (motion-color paradigm). The second line (stars) represents the results of Experiment 2d (dynamic color-orientation paradigm), the third line (diamonds) the results of Experiment 2c (color-orientation paradigm), while the lower line (squares) represents the results of Experiment 2b (motion-orientation paradigm). A negative SOA indicates the time interval between the change of the first feature (indicated by the paradigm name) and the other feature change, whereas a positive SOA means an opposite feature change order.

Although the order of the conditions in terms of overall RTs differed slightly between detection and conjunction tasks, targets in static color-orientation and motion-orientation trails were identified faster than in motion-color and dynamic color-orientation conditions. This result suggests that, independently of the task requirements, an orientation change leads to a generally faster response than a color change. However, in conjunction tasks, motion seems to have less of an influence than in detection tasks.

The fact that the longest RTs were consistently observed when both features changed simultaneously does not imply that both features are processed at the same speed. In a conjunction task the target cannot be recognized before the last feature is identified. In the case of a synchronous change, the identities of both features have to be accessed at the same time, resulting in an overload of the cognitive system and a slowing down of the identification process. An asynchronous change, however, leads to faster target identification because processing dual features does not overlap in time. The feature that changes first is already (at least partially) processed before the second feature is available for identification. The time during which feature processing overlaps is reduced as a function of the SOA length.

According to this reasoning, the processing overlap is always maximal when features change simultaneously, independently of the relative processing speed of the features involved. However, the magnitude of the detection time decrease as a function of the SOA is influenced by the asynchronicity of feature processing speeds. As depicted in Panel a of Figure 3.22, when both features have the same processing speed, their overlap zone (hatched area) decreases at the same rate regardless of which feature changes first. The resulting slopes for positive and negative SOAs are therefore similar. In the case of asynchronous processing speeds, the processing overlap zone decreases differently according to the feature that changes first. As depicted in Panel b of Figure 3.22, when the fastest processed feature changes first, a faster reduction of the overlap zone is observed than when the slowest processed feature changes first. The slope representing the RT gain as a function of the SOA length for the fastest processed feature is consequently steeper than for the slowest one.

According to this assumption, the RT slopes (as a linear function of the SOA) were computed for each feature in each condition. In the motion-color condition, RTs were reduced significantly more when the motion feature changed first (*M* = -.8 ms, *SD* = .3 ms) compared to when the color feature changed first (*M* = -.4 ms, *SD* = .2 ms, *t*(9) = 4.99, *p* < .001). However, in the motion-orientation condition, the slope was steeper when orientation changed first (M= -.6 ms, *SD* = .2 ms) than when motion changed first (*M* = -.4 ms, *SD* = .1 ms; *t*(9) = 2.87 ,*p* < .05). Finally, although slopes for orientation (static display: *M* = -.5 ms, *SD* = .4 ms; dynamic display: *M* = -.6 ms, *SD* = .3 ms) were steeper than slopes for static color displays: *M* = -.4 ms, *SD* = .4 ms; dynamic display: *M* = -.6 ms, *SD* = .3 ms) in both color-orientation paradigms, they did not differ significantly (static display: *t*(11) = 1.30, *p* > .10; dynamic display: *t*(11) = .77, *p* > .10).

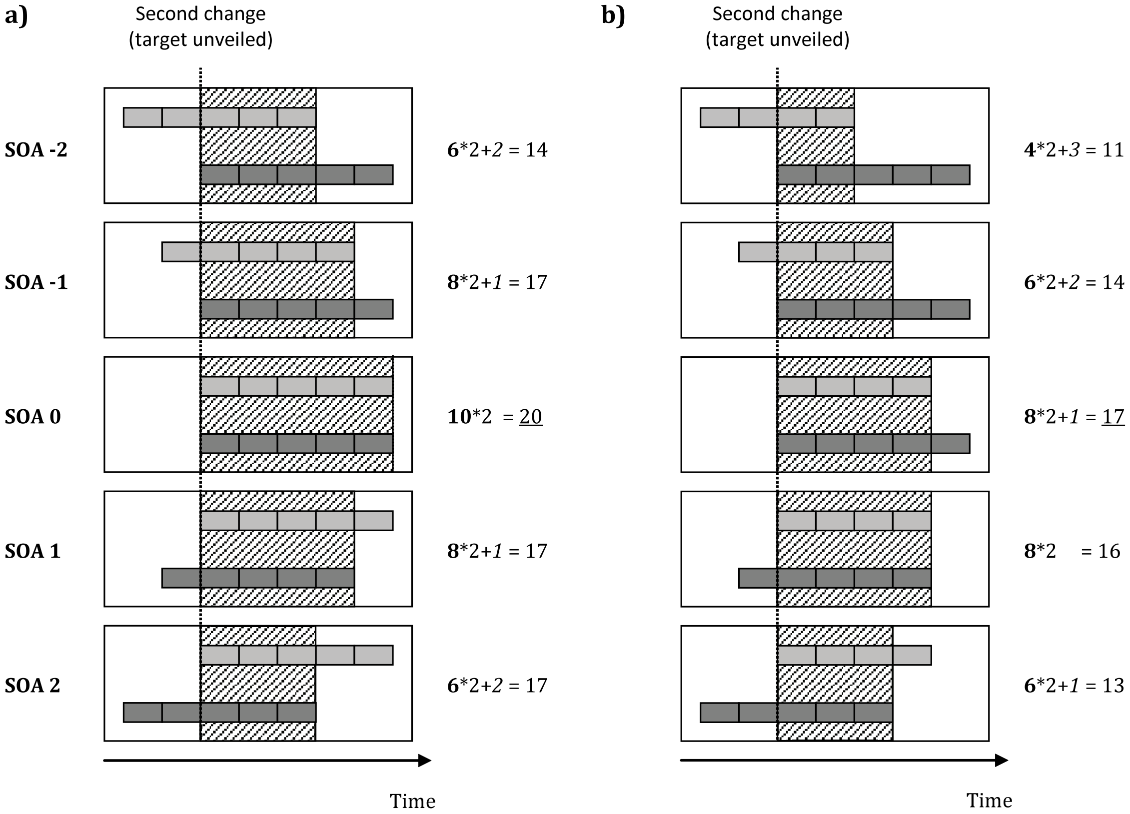

Figure 3.22. Schematic representation of the influence of feature processing speed on SOA-curve in conjunction task. A negative SOA indicates that the light grey feature changed first, whereas a positive SOA indicates the dark feature change first. Features are represented by the segmented (light and dark) grey bars corresponding to the time required to identify a feature. The streaked area indicates a feature processing overlap. In this case, processing speed for both features is slowed down (represented by the bolder segments). The calculation at the right of each picture represents the arbitrary time (in bar segments) needed to process both features after the second feature change (dotted line). Bold numbers correspond to the number of segments in the overlap zone (arbitrary multiplied by two to symbolized the slowing down) and italic numbers the segments to be processed after the overlap. **Panel a**) When features have the same processing speed, the amount of processing time diminished at the same rate, independently of which feature changes first (see calculation). Slopes indicating the RT gain for negative and positive SOAs are consequently identical. **Panel b**) When features present different processing speeds, the RT gain generated by the SOA differs according to the feature. The fastest processed feature has a steeper slope than slowest one (see calculation). However, in both panels, the longest remaining processing time is observed at SOA 0 (underlined numbers).

The fact that some slopes were not statistically equivalent in particular feature combinations suggests an asymmetry in the feature identification speed. In the present Experiment 2, color and orientation seem to be processed at the same speed regardless of the dynamic properties of the display (Experiment 2c and d). Nevertheless, the steeper slope for motion suggests that this latter is processed faster than color, whereas orientation is processed faster than motion.

Finally, to investigate whether the nature of the feature that changed first influenced the processing of the feature that change in a second time, slopes for the same feature were compared across paradigms. Two separate one-way ANOVAs revealed no significant difference between the slopes for an initial change of color ($F(2,29) = 1.42$, $MS_e = 2.77$, $p > .10$) or orientation ($F(2,29) = .32$, $MS_e = 2.62$, $p > .10$) in the three different paradigms involving color or orientation. However, the slope for motion was steeper in motion-color than in motion-orientation paradigm ($t(18) = -4.33$, $p < .001$).

Slope analysis within and between paradigms revealed that color and orientation are processed at the same speed in a feature change conjunction task independently of the feature combination. However, motion identification seems to be modulated by the feature that has to be processed at the same time; motion is processed faster when paired with color than with orientation.

3.14. General discussion

This study was aimed at investigating the somewhat neglected temporal integration of visual features in a search task involving targets defined on two dimensions under two different task requirements. In the first set of experiments (Experiments 1a to d), participants were instructed to react to any feature change in the display (detection task), whereas, in the second set of experiments (Experiment 2a to d), they had to react to specific predefined combinations of feature changes (conjunction task). Feature changes were separated by variable temporal asynchronies (SOA), a manipulation permitting to gauge the relative temporal contributions in both tasks.

Experiment 1 showed that, in a detection task the optimal temporal feature integration did not necessarily occur when features changed simultaneously. Motion and orientation had to change 20 ms before color to be integrated optimally. This result provides a suitable explanation to the lack of the RMI violations for some specific feature combinations observed in previous researches (Koene & Li, 2007; Poom, 2009). RT distributions analyses revealed RMI violations for targets defined by a combination of motion and color at some of the tested SOAs. Based on these findings, a modified version of contrast summation models (e.g., Wolfe, 1994) integrating a difference in feature processing speed was proposed (see Figure 3.15).

In addition to processing speed related feature integration, Experiment 1 provides some evidence that visual features are processed in parallel but not fully independently. The fact that a moving target defined either by its color or orientation is detected faster in a condition where motion is a target feature than in a condition in which motion is task-irrelevant suggests some reciprocal influence of the processed features.

Experiment 2 confirmed that the temporal integration of visual features differed under conjunction task requirements (Schönwälder, 2006). Performing conjunction tasks in Schönwälder’s (2006) and the present study requires a deeper feature processing than in a detection task. In conjunction tasks the target cannot be recognized before the last feature is available for identification (i.e., before the last feature change). Results demonstrated that the longest RTs were systematically observed when features changed simultaneously and that RTs systematically decreased with increasing SOA. This finding can be explained by a reduction of the processing overlap as a function of SOA length. In the case of synchronous changes, both features compete for access to feature value analysis at the same time, resulting in an overload of the cognitive system and slowing of the identification process. Asynchronous changes, however, lead to faster target identification because the feature processing overlap is reduced. The feature that changes first is already (at least partially) processed before the second feature change. In this case, the time during which feature processing overlaps is reduced as a function of the SOA size.

As mentioned above, regardless of the processing speed of the paired features, the maximal processing overlap is constantly observed when features change simultaneously. However, the processing speed influences the slope generated by the SOA. Features with a similar processing speed produce equivalent slopes, whereas the fastest processed feature generates a steeper slope than the slowest one (see Figure 3.22).

Detection versus conjunction task

Results of Experiments 1 and 2 reveal that temporal feature integration depends on the processing depth required to solve the task. As reported by Treisman and colleagues in the classical procedure of the conjunction task (e.g., Treisman & Gelade, 1980; Treisman & Sato, 1990) and by Schönwälder (2006) in a change paradigm, results of the present experiments show that a deeper feature processing (i.e., feature identification) requires more time than a feature detection; the RT grand mean in detection task was significantly shorter than in conjunction task for all paradigms (see t-tests in the last column of Table 3.11).

Furthermore, as already reported by Schönwälder (2006), introducing a time interval between feature changes does not have the same impact on detection and conjunction tasks. More precisely, these tasks generate inverted RTs patterns. RTs in a detection task increase from a minimum that varies according to the combined features, whereas, in a conjunction task, they decrease from a maximum that is systematically localized at a simultaneous feature change.

Table 3.11

Comparison of RT grand means in detection and conjunction tasks in each paradigm.

Paradigm	Task				
	Detection		Conjunction		T-test
Motion -color	349.58	(28.10)	629.64	(82.94)	t(11.04) = 10.11, p < .001***
Motion - orientation	329.82	(26.69)	499.93	(46.47)	t(18) = 10.11, p < .001***
Static color - orientation	308.48	(35.82)	537.66	(77.46)	t(15.50) = 9.30, p < .001***
Dynamic color -orientation	378.42	(16.12)	612.77	(60.71)	t(10.62) = 11.80, p < .001***

In addition, the way features are integrated differs between detection and conjunction tasks. An adapted contrast-map summation model seems to explain at best the results in detection task, whereas, some findings suggest the amount of processing overlap is responsible for the RT decrease according to the time interval size in conjunction task. However, both models take feature processing speed into account. This factor contradicts Ulrich and Miller's (1997) predictions demonstrating that an optimal feature integration should occur when both features change simultaneously, but, among others, Moutoussis and Zeki (1997 a, b) provide some evidence that visual features are not processed at the same speed when they have to be integrated.

The relative processing speed of the to-be-integrated features seems thus to be the key for the results observed in both tasks employed in this study. Further research on the temporal feature integration is required to confirm (or infirm) the validity of both models outlined in the present work.

4. Investigating the mechanism underlying visuo-auditory integration in visual search: Evidence from temporal variation of signal onsets

4.1. Abstract

In a number of recent studies investigating visual search for singleton feature targets (e.g., Krummenacher, Müller & Heller, 2001, 2002a, 2002b) it was shown that targets differing from distractors by two features (redundant target) are detected faster than targets differing from distractors by only one feature (single target). The reaction time (RT) advantage is referred to as "redundancy gain". A plausible explanation for redundancy gains is that the features are processed in a parallel co-active way, namely feature contrast saliency activation of both features is integrated in a module that triggers the response; by integration an activation threshold that must be exceeded to trigger response execution is reached earlier in time and hence reactions to redundant targets are expedited. The present study investigates whether, in a search task, cross-modal feature integration is controlled by a mechanism similar to the one that underlying integration of visual features. To examine the issue, two detection tasks were conducted using a visuo-auditory paradigm. The display used dynamic changes, namely participants had to pay attention to visual and auditory feature changes. In trials with dual (redundant) feature changes, both changes occurred simultaneously (Experiment 1) or were separated by variable stimulus onset asynchronies (Experiment 2). Both experiments revealed expedited detection of redundant relative to non-redundant feature changes. The findings provide evidence for feature integration by a co-active mechanism. Co-active processing of visual and auditory features follows a fixed sequence, for co-active processing to occur visual feature changes must take place simultaneously with or precede auditory feature changes by up to 40 ms. The finding of this temporal window of integration is coherent with the results of studies on simultaneity perception judgments and with neurophysiology data demonstrating that auditory signals are processed faster processed than visual signals.

4.2. Introduction

Lots of operators have to constantly scan consoles to be able to detect and react, as quickly and accurately as possible, to critical changes in display elements. To make this task easier, the target display objects might be made highly distinguishable from other displays. In visual search, targets that are detected rapidly because of their featural or dimensional contrast to surrounding (distractor) elements are called *pop-out* targets (e.g., Treisman, 1988). Recent investigations (e.g., Krummenacher, Müller & Heller, 2001, 2002a, 2002b) observed that, in visual search, redundantly defined targets (e.g., a red vertical bar) presented among homogeneous distractors (e.g., green horizontal bars) were detected significantly faster than singly defined targets (e.g., a red horizontal bar or a green vertical bar). The expedited RTs for redundantly defined objects were termed redundancy gains, or the redundant signals effect (Raab, 1962).

An explanation for the redundancy gain phenomenon can be found either in statistical facilitation of signals processed in a parallel race (Raab, 1962) or parallel and co-active processing of signals (Miller, 1982). Both models assume that features are processed independently and in parallel, however, they diverge in their assumptions about the mechanism underlying the triggering of responses. Raab's (1962) *parallel race model* postulates that there is competition between signals (features) in which the first fully processed signal (i.e., winner of the race of signals) triggers the response. Assuming that RT distributions for the detection of singly defined targets overlap, each feature is expected to win the race in some trials. Detection time for redundantly defined objects is therefore determined by the faster of the two signals and, consequently, due to statistical facilitation, RTs to redundantly defined targets are, *on average*, faster than RTs to non-redundantly defined targets.

On the other hand, Miller (1982) suggests that the response is triggered by the pooled activation of signals (features); two (or more) independent signals contribute to the generation of activation in a joint module that triggers the response, hence the term parallel co-active processing. Miller (1982) proposed a test to differentiate parallel race models from parallel co-active processing architectures. The test is based on the entire RT distributions and is referred to as the race model inequality (RMI). According to the RMI, processing models postulating a parallel race of signals to trigger the response must satisfy the following inequality: $F_R(t) \leq F_{T1}(t)+ F_{T2}(t)$; where t is the time since display onset and F the RT cumulative function, T1 and T2 correspond to reaction times of signals (features) 1 and 2, and R represents the redundantly defined target R (composed of signals 1 and 2). The term to left of the inequality sign corresponds to the cumulative probability of a response having occurred at a time t after display onset to a redundant target. The term to the right of the inequality sign refers to the sum of the cumulative probabilities of a response to a non-redundant target having occurred at a time *t* after display onset. Critically, the (summed) probabilities of RTs to non-redundant targets at time t must not be smaller than the probability of RTs to redundantly defined targets at time t for the assumption of a parallel race model to hold. Violations of the race model equality, that is, smaller than expected summed reaction time probabilities to non-redundant targets, provide evidence in favor of a parallel coactive processing.

Applying Miller's (1982) RMI procedure, Krummenacher et al. (2001, 2002a, b) observed RMI violations for redundantly defined visual targets. Visual features in search tasks are processed in a parallel coactive way. One subsequent question is whether the mechanism controlling feature processing in purely visual (detection) tasks can be generalized to the other sensory modalities. Studies using onset detection tasks (i.e., tasks, in which participants are instructed to react to any stimulus onset as quickly as possible) showed RMI violations for multisensory stimuli (Arndt & Colonius, 2003; Colonius & Arndt, 2001; Diederich & Colonius, 2004; Hughes, Reuter-Lorenz, Nozawa & Fendrich, 1994; Miller, 1982, 1986). In one recent study (Forster, Cavina-Pratesi, Aglioti & Berlucchi, 2002), participants were instructed to react to any visual or tactile stimulus onset. Stimuli were either (uni- or bilaterally) bimodal, (uni- or bilaterally) dual unimodal, and single unimodal. Results demonstrated robust redundancy gains and RMI violations with single bimodal targets and dual unimodal visual stimuli; however no RMI violations were found for dual unimodal tactile stimuli. Patching and Quinlan (2004), in a study using a double-factorial (modality: auditory/visual; intensity; high/low) design in a simple detection task, also reported redundancy gains and RMI violations. Altogether, these findings suggest that multisensory onset detection is processed parallel coactive in nature.

However, in the experiments outlined above, the non-redundant or redundant stimuli were displayed in isolation, namely presentation involved one or two stimuli; that is, as observers did not have to search for the relevant information, the selective attention component was not investigated in these tasks, rather, pure perception was examined. Conditions in which stimuli are presented in isolation are very rare in everyday life; in other words, selection is almost always part of perception. In the tasks used in the cited studies, selection did not to take place, only object detection. To take aspects of selection in account, the present study investigated visuo-auditory integration under search conditions. Furthermore, with a view toward ecologic validity, dynamic search tasks were used, reflecting the fact that searches often occur under dynamic conditions.

4.3. Experiment 1

The purpose of Experiment 1 was to investigate the processing of visuo-auditory feature changes under search conditions. An array of bars was used as visual stimuli while a pure tone served as the auditory stimulus. During each trial, either one of the bars, the tone, or both the visual and the auditory stimulus changed. Participants' task was to detect any of the changes as quickly as possible.

4.3.1. Method

Participants. Twelve students (six female and six male), all students at the University of Fribourg participated in Experiment 1. They were between 22 and 28 years old (*M* = 23.3, *SD* = 1.71). Observers had normal or a corrected to normal vision, including normal color vision; they did not report any auditory problems.

Design. Each trial started with a 200 ms blank followed by a fixation cross (0.4°x 0.4° visual angle) presented for 500 ms. Immediately after extinction of the fixation cross, the search display composed of 49 green bars appeared together with a 200 Hz tone. Three different sequences of events could follow (see Figure 4.1 for illustrations): (a) a change occurred in one of the (visual or auditory) features, (b) a change occurred simultaneously in the two (visual and auditory) features, or, (c) there was no change during the whole of the trial. If there were change(s), the first one occurred after a delay of between 800 to 1200 ms (five steps separated by 100 ms). The participants were given a maximum of 1500 ms to react in go trials. When this time had passed, the next trial began. In the no-go trials, the display did not change and the participants were instructed to refrain from any response and to wait for the next trial to begin. In go trials, either the color of one bar (color condition), the sound (sound condition), or both the color and sound changed (redundant, color and sound change condition). In the color condition, the color of one bar changed (from green) into red (RGB code: 255, 0, 0) or blue (RGB: 0, 0, 255); in the sound condition, the frequency of the tone was either decreased (to 100 Hz) or increased (to 300Hz).

Stimuli. Visual stimuli were 49 green vertical bars subtending 0.38° x 1.15° of visual angle presented on a black background (RGB: 0,0,0). Because of the subjectively important difference between hues (e.g., Folk, Remington & Johnston, 1992), color isoluminance was not aimed at (RGB green: 0, 255, 0). The bars were displayed in a virtual 7x7 (rows x columns) matrix subtending 13.56° x 14.25° of visual angle. The position of each item relative to the center of its matrix cell was randomly jittered in each trial (±0.19° along the horizontal and vertical axes, respectively) to prevent collinearity with the other stimuli.

*Apparatus and setting***.** Participants were seated at a distance of approximately 50cm from the Philips Brilliance P202 19” monitor controlled by a HP Compaq Business Ultra Slim Desktop Dc7600 personal computer (Pentium IV at 3.2 GHz, 512 Mb RAM). The monitor resolution was set to 1280x1024 pixels and its refresh rate to 100Hz. The tones were diffused through Sennnheiser head max px 30 headphones. Experiment 1 was programmed using MatLab and Cogent 2000 developed by the Cogent 2000 team at the FIL and the ICN and Cogent Graphics developed by John Romaya at the LON at the Wellcome Department of Imaging Neuroscience. The Experiment was conducted in a darkened room.

Procedure. In a first session participants were familiarized with all possible experimental trials they would encounter during the experiment (there were nine different single and redundant target trials); familiarization was followed one “warm-up” block of 24 trials, followed by 12 experimental blocks of 40 trials. The whole experience took about 45 minutes to complete. The participants were instructed to react as quickly as possible to each change of the display or sound by depressing the space bar of the keyboard with their dominant hand; they were also instructed to avoid making errors. Instructions are presented on the screen at the beginning of the experiment and participants were instructed orally by the investigator. The “warm-up” block comprised 8 no-go trials, 4 color change trials, 4 sound change trials and 8 redundant (color and sound change) trials. After each trial of the familiarization block, a feedback indication whether the participant's response was correct or not was displayed on the screen; responses were not recorded. No feedback was given in experimental blocks. Each experimental block contained 16 no-go trials, 8 color, 8 sound, and 8 redundant trials. At the beginning of each block, the block number was shown to inform observers of the progress, and participants had to depress the space bar to initiate the block. A total of 480 recorded trials were presented with trial types (absent-, color, sound, and redundant) chosen in a randomized order.

4.3.2. Results and discussion

In a first analysis, mean RTs analysis and redundancy gains will be presented, followed by test for violations of the RMI. The findings are discussed in the last part of the present section.

To avoid confounds by anticipatory and extremely slow responses, RTs shorter than 200ms and longer than 800ms were excluded (note that the 800 ms limit was chosen in function of the individual overall reaction time distributions). RTs, namely RTs exceeding three standard deviations of the mean, for each observer and each condition, were also excluded from analysis. Miss rates (see Table 4.1) did not differ significantly across the three present-target types ($F(1.33,14.57) = 1.19$, $MS_e = .011$, $p > .05$). (Note that pair-wise comparisons were adjusted using the Bonferroni correction where necessary.)

Mean reaction times and redundancy gains. The mean reaction times are presented in Table 4.1. The results show significant difference between target types ($F(2,22) = 82.30$, $MS_e = 342.33$, $p < .001$); multiple comparisons indicated that redundant trials ($M = 353.87$ ms, $SD = 51.65$ ms; $t(11) = 14.55$, $p < .001$) were responded to significantly faster than *color* trials ($M = 405.92$ ms, $SD = 53.82$ ms), and color trials were responded to significantly detected than *sound* trials ($M = 448.69$ ms, $SD = 70.30$ ms; $t(11) = 4.45$, $p < .01$).

RTs to redundant targets were on average 75 ms faster than the averaged single target RTs ($Gain_{Avg}$, t(11) = 18.32, p < .001). Testing averaged gains assumes there is no difference between single target RTs. According to Biederman and Checkosky (1970), it could be that all observers prefer one and the same signal, in the present case the color signal. Redundancy gains according to the fixed-favored feature assumption (referred to as GainB&C) shows a 53.9 ms redundancy gain (t(11) = 9.18, p < .001). As the fixed-favored feature assumption might, however, be incorrect, because individual signal preferences could differ or there might be no preference at all, Miller and Lopes (1988) proposed an alternative solution to deal with the favored-signal problem. Miller et al. (1988) compare the mean RT of the singly-defined targets, individually for each observer. If RTs differ significantly (by a liberal criterion of α = .10), the faster of the single RT is used to assess redundancy gains, if single RTs do not differ, the overall mean RT from the single features is used for comparison with redundant trial RTs. Measuring redundancy gains according to the Miller and Lopes (1988) procedure (referred to as GainM&L) yielded a significant overall redundancy gain of 52.2 ms (*t*(11) = 8.75).

Table 4.1

Mean correct reaction times (RT), misses percent for each target type and redundancy gains for redundant targets according to the three procedures.

	RT (ms)		Miss (%)		Redundancy gains (ms)					
					$\text{Gain}_{M\&L}$		Gain_{Avg}		$\text{Gain}_{B\&C}$	
Sound	448.69	(70.30)	0.05	(0.13)						
Color	405.92	(53.82)	0.00	(0.00)						
Redundant	352.00	(51.65)	0.02	(0.06)	52.16	(20.65)	74.55	(14.10)	53.92	(20.34)

Note. Mean reaction time redundancy gains relative to the faster of the two single-feature ($\text{Gain}_{B\&C}$ and $\text{Gain}_{M\&L}$) and relative to the average of the two single feature targets (Gain_{Avg}). $_{B\&C}$ = Biederman and Checkosky (1970). $_{M\&L}$ = Miller and Lopes (1988).

RT distributions analysis. Miller's (1982) Race Model Inequality (RMI) allows differentiating parallel co-active processing architectures from strictly parallel race processing of redundantly defined targets. The results of the tests for violations of Miller's RMI are shown in Figure 4.2. Following the analyses by Krummenacher et al. (2001, 2002a, b), the summed cumulative RT function of singly defined targets ($F_{T1}(t) + F_{T2}(t)$) was calculated for a set of response times, t, that corresponded to the 5% quantiles (5th, 10th, 15th percentile, etc.) of distribution of RTs to redundantly defined targets Violations of the RMI were tested for statistical significance for each quantile, using t-tests. Miller's RMI is violated if the summed cumulative RT function for color and sound targets is smaller than the cumulative RT function for redundant targets. The results revealed fourteen significant violations of the RMI (from quantiles .05 to .70) were, providing evidence that features changes occurring in different sensory modalities in search tasks, are integrated in a parallel coactive fashion.

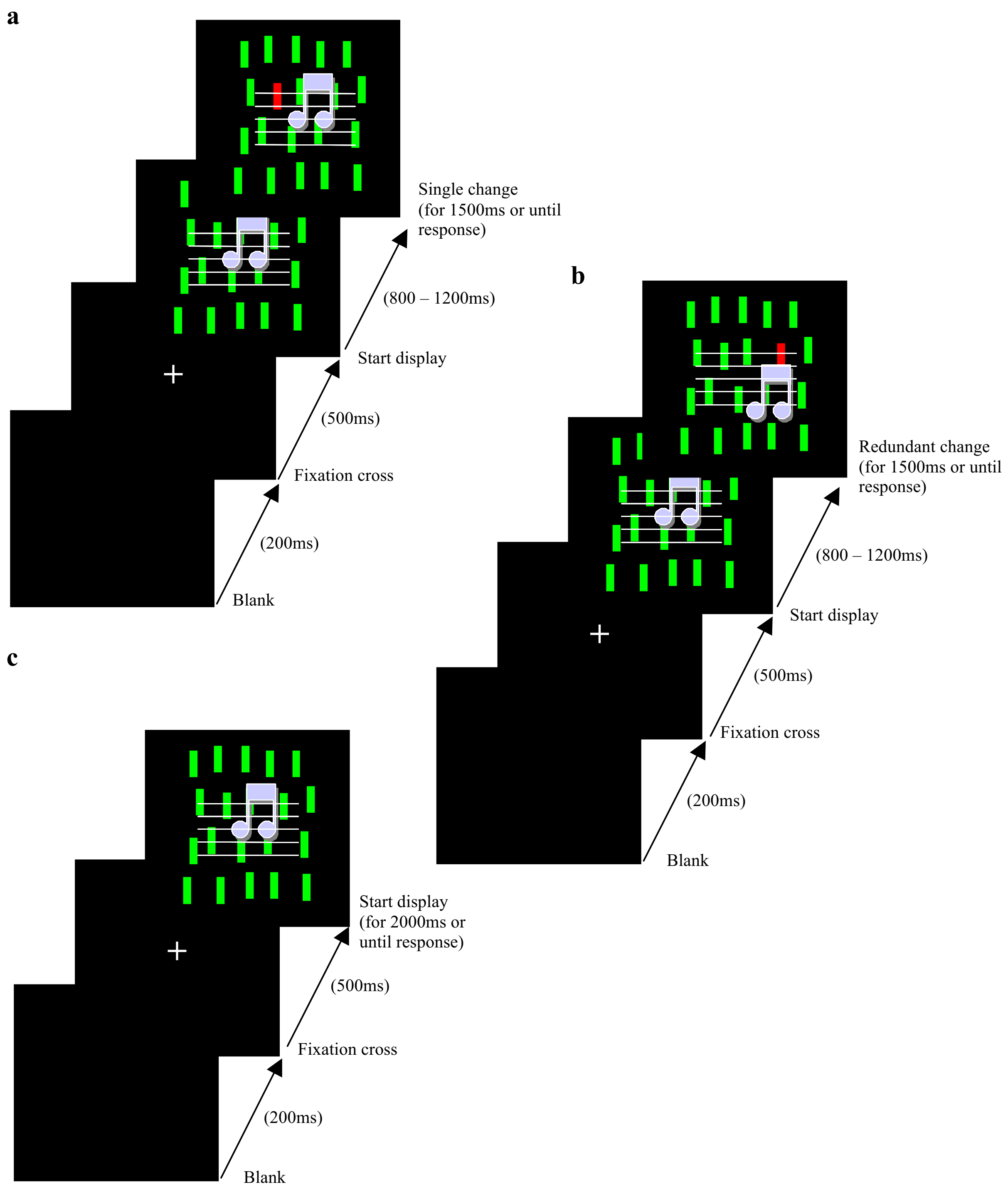

Figure 4.1. Schematic (and not to-scale) representation of the conditions and sequence of events in Experiment 1. **Panel a** represents a single feature change trial (either color or sound); **panel b** stands for a redundant feature change trial; **panel c** represents a no change trial.

Altogether, results of Experiment 1 replicate previous findings concerning auditory-visual integration (Arndt & Colonius, 2003; Colonius & Arndt, 2001; Diederich & Colonius, 2004; Hughes et al., 1994; Miller, 1982, 1986; Patching & Quinlan, 2004). Redundancy gain analyses revealed that bimodal change was faster detected than a unimodal change. Furthermore, violations of Miller's (1982) RMI provide evidence that visuo-auditory stimuli are processed in a parallel coactive way. This suggests thus that the initially separate activations generated by the processing of stimulation of different sensory modalities are combined in order to create a strong coherent representation of the environment. Interestingly, the visuo-auditory search paradigm used in Experiment 1 showed that the RMI was violated in 14 (out of 19) quantiles. In contrast, in the visual-visual (color, orientation) search task used by Krummenacher et al. (2001, 2002a, b) violations in found two to six violations quantiles were found. Because of the variations in the experimental procedures and the differences in the way violations of Miller's RMI are reported in the literature, a quantification of the number of observed violations in experiments using multisensory stimuli is not without problems. Nevertheless, the number of quantiles in which violations were observed serves a rough estimate of the magnitude of the RMI violations and hence the present findings, at the very least, suggest that RMI violations are easier to find in tasks involving multisensory integration.

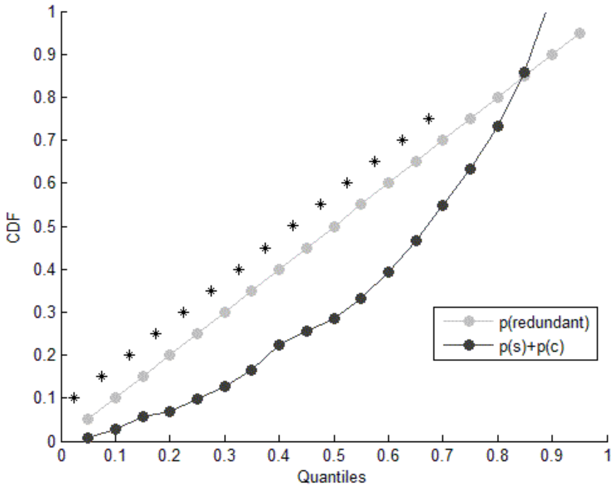

Figure 4.2. Results of the tests for violations of Miller's (1982) RMI in Experiment 1. The dark grey curve represents the cumulative probability function for the summed probabilities of RTs to single targets having occurred at a given time t; the light grey curve represents corresponding redundant target probabilities. Significant violations are marked with a star (*p* < .05). Note that for the RMI to be satisfied, summed single dimension probabilities must be no smaller than redundant target probabilities.

One major difference between previous multimodal experiments and the present study are the task requirements. First, in all the previous studies, participants had to detect stimulus onsets, whereas, in the present Experiment 1, participants had to react to a change in visual and/or auditory stimulation. Second, the number of stimuli during a trial is different. In previous studies, an equal number of stimuli per modality were presented, namely one visual and/or one auditory stimulus. In Experiment 1, however, the ratio between auditory and visual stimuli was unbalanced; in detail, participants faced an array of visual stimuli, one of which, in target-present trials, would change (a situation comparable to a feature singleton search tasks), while only one auditory stimulus was presented through the earphones. The setting thus involved search for a visual change and detection of an auditory change. Although pop-out visual search tasks are commonly assume not to require attention (e.g., see Treisman & Gelade, 1980), it is possible that the detection of the change of one visual stimulus among many others required a larger amount of attentional resource than the detection of the change of a single auditory signal. It is thus possible that participants primarily focused processing on visual stimuli. A consequence of such an unbalanced attention allocation could be that RTs for single auditory stimuli are higher than for single visual stimuli, the pattern found in the Experiment 1. Along the same lines, the redundancy gains observed in the present experiment might be interpreted as an enhancement of the visual detection by an auditory “accessory” stimulus. Note that this idea reflects the assumption of co-active processing, in which a relatively slower or weaker signal expedites processing of a faster or stronger signal. Note also that this assumption implies that visual and auditory modalities share a common, limited, pool of attentional resources.

Enhancement of visual perception by auditory stimulation as outlined above was reported by Vroomen and de Gelder (2000). In a series of experiments, they presented visual displays, each of which consisted of four briefly presented frames. Each frame, composed of a pattern of four dots, was accompanied by a tone and followed by a mask. In one of these frames, a target pattern was displayed, and participants’ task was to indicate its spatial location. The frame sequence was repeated until participants had responded. Vroomen et al. showed that the probability of identifying the correct target position increased when the tone displayed with the target frame was different from the tone accompanying the other frames. Furthermore, participants reported a freezing illusion, in which the target frame seemed to last longer than distractor frames. The detectability of a flashed light followed by a mask can be also enhanced when a sound is presented simultaneously with the target flash (Frassinetti, Bolognini & Làdavas, 2002). Finally, recently it was shown, that a synchronous task-irrevelant sound could facilitate the detection of a visual target (Van der Burg, Olivers, Bronkhorst & Theeuwes, 2008). In the Van der Burg et al. study, participants had to indicate whether a vertical or horizontal bar was present in an array of tilted bars. All display items altered independently from green to red at their own speed during the whole trial. The target kept its color for on average 900 ms and, when it changed, it was the single item in the display to do so. A sound (”bip”) accompanied half of the trials. Results showed, first, a RT decrease in trials with sound. Second, the search times were optimal when the bip sounds were synchronous with target color changes. These results in general and the Van der Burg et al. (2008) study in particular, suggest that the additional (irrelevant) tone enhances the target to distractor contrast.

4.4. Experiment 2

The results of Experiment 1 suggest that it might be more difficult to detect auditory than visual targets, still, RT redundancy gains and violations of Miller (1982)’s Race Model Inequality were observed, providing clear evidence that multisensory integration is parallel and co-active in nature. One further restriction should be noted: Feature changes in the visual and auditory domain were simultaneous in Experiment 1. Behavioral experiments focusing on the temporal integration of multimodal stimuli demonstrated that auditory and visual stimuli are perceived as simultaneous when the visual stimulation precedes the auditory stimulation by up to 80 ms, depending on the paradigm (Slutsky & Recanzone, 2001; Spence, Baddeley, Zampini, James & Shore, 2003; Stone et al. 2001; Zampini, Shore & Spence, 2003; Zampini, Guest, Shore & Spence, 2005). These observations lead to the assumption that visual features need more time to be processed than auditory stimuli. The idea of a temporal difference in processing times is also supported by human intracranial recordings, showing that, when displayed simultaneously, visual inputs reach the superior parietal lobe (a cortical multisensory integration region [see e.g., Avillac, Hamed & Duhamel, 2007; Calvert, Hansen, Iversen & Brammer, 2000]) about 30 ms after auditory inputs (Molholm et al., 2006).

According to these results, optimum visuo-auditory integration should be observed when the visual change appears before the auditory change in time range between 0 to 80 ms. To test this hypothesis, a stimulus onset asynchrony (SOA) was introduced between auditory and visual changes in redundant change trials of Experiment 2.

Using a similar dynamic search paradigm, Schönwälder (2006) investigated the temporal integration of odd items defined by their color and motion (i.e., two visual dimensions). In Schönwälder's detection task, green bars were moving from the left to right side of the monitor, or vice versa. After a variable time one (single color or single motion change) or two features (redundant color and motion change) of one of the display items changed. Observers had to report any change as quickly as possible. Results showed that the redundantly defined targets were detected significantly faster than single targets. More importantly, Schönwälder found the reaction times increased with the size of the time interval between features changes, a finding also reported by Heath (1984). In other words, the longer the time interval between feature changes, the slower reaction times.

In the multisensory domain, Diederich and Colonius (2004) used a SOA between the onset a visual (a flash) and an auditory stimulus (a tone) and reported a greater facilitation effect in the detection of visuo-auditory target onset when the flash preceded the tone by 10 to 30 ms. However, due to technical reasons, they could not display the tone before the flash. Although behavioral data and neurophysiology strongly suggest delayed processing for visual stimuli (in comparison to auditory signals), the setting of Experiment 2 allowed to test, simultaneously, both this and the opposite assumption.

In order to balance the attention allocated to each stimulus type, the green bars were replaced by crosses made up of small red and green squares. When a visual change occurred, all crosses changed simultaneously and the target was defined by its color uniqueness (namely, one cross turned to red and all others to green, or vice versa).

4.4.1. Method

Participants. Fourteen observers (all female) took part in Experiment 1. All were students at the University of Fribourg. They received course credits for their participation. They were aged between 18 and 37 years (*M* = 21.4, *SD* = 4.8). All observers had normal or a corrected to normal vision, including normal color vision.

Design. Each trial started with a blank of 500 ms, followed by the simultaneous presentation of the cross visual stimuli and the tone. Three different sequences could follow (see Figure 4.3 for illustrations): (a) a change occurred in one of the features (visual change or auditory change), (b) a change occurred in both the visual and the auditory features, separated in time by a variable SOA (seven different stimuli onset asynchronies were used: -60, -40, -20, 0, 20, 40, 60 ms), or (c) there was no change at all during the whole trial. If there was (were) change(s), the first change occurred after a delay of 800 to 1200 ms (five steps separated by 100ms). Participants were given a maximum of 1500 ms to respond. In order to compensate for the variable delay before the first change (in trials with in which a change occurred), displays were presented for 2000 ms in trials in which no change occurred. After the maximum presentation time had elapsed or when observers had responded, the next trial began with an intertrial interval.

*Stimuli***.** Visual stimuli were 36 x-shaped crosses subtending 2.3° x 2.3° of visual angle presented on a black background and made up, initially, of small red and green squares. Because of the subjectively important difference between hues (e.g., Folk, Remington & Johnston, 1992), color isoluminance was not aimed at (RGB code for red: 255, 0, 0, and for green: 0, 255, 255). Those crosses were displayed in the cells of virtual 6x6 (rows x columns) matrix that subtended 16.73° x 16.73° of visual angle. The position of each item relative to its matrix cell center was randomly jittered in each trial (maximally ±.67° along the horizontal and vertical axes, respectively) to prevent collinearities with other stimuli. The auditory stimulus was a pure tone of 200 Hz. In the no-go trials, the audio-visual display did not change, and the participants were instructed to refrain from responding and to wait for the next trial to begin. In go trials, either the color of the crosses changed (the color of one cross changed to red and the color of the other ones to green, or vice versa; color condition), the tone frequency decreased (to 100Hz) or increased (to 300Hz) (sound condition), or both the color and the tone frequency changed as in the respective single change conditions (redundant condition).

In the redundant condition, the onsets of the two feature changes were either synchronous (SOA = 0 ms) or asynchronous, with SOAs varying between -60 ms to +60 ms in steps of 20 ms. Including the 0 ms SOA, seven SOAs conditions were used in redundant change trials of Experiment 2 see Figure 4.3). The minus (-) sign before the onset asynchrony time signifies that the tone changed first, while the plus (+) indicated that color first changed, followed by the respective other feature change. The SOA values were chosen arbitrarily, but taking into account the screen refresh rate of the monitor (100 Hz). RTs were recorded from the beginning of the first change. To avoid edge effects, targets were presented in the inner 4x4 cells of the virtual grid.

Figure 4.3. Design of Experiment 2. **Panel a** represents a single feature change trial (either color or sound). **Panel b** stands for a redundant feature change trial, in which feature changes are separated a certain time interval (SOA). **Panel c** represents a no change trial.

*Apparatus and setting***.** Participants were seated at a distance of approximately 50 cm from the Philips Brilliance P202 monitor controlled by a HP Compaq Business Ultra Slim Desktop Dc7600 personal computer (Pentium IV at 3.2 GHz, 512 Mb RAM). The monitor resolution was set to 1024x768 pixels and its refresh rate to 100Hz. The tones were presented through Sennnheiser head max px 30 headphones. This experiment was programmed using MatLab and Cogent 2000 developed by the Cogent 2000 team at the FIL and the ICN and Cogent

Graphics developed by John Romaya at the LON at the Wellcome Department of Imaging Neuroscience. The experiment was conducted in a darkened room.

Procedure. Participants completed 1 “warm-up” block of 24 trials and 7 experimental blocks of 112 trials. The whole experiment took about 45 minutes to complete. Participants were instructed to respond as quickly as possible to any change in the visual display or tone by depressing the space bar of the keyboard with their dominant hand (go trials). The instructions were presented on the screen at the beginning of the warm-up block and the experimental blocks. Participants were also instructed orally by the investigator. The warm-up block contained 6 no-go trials, 6 color trials, 6 sound trials and 6 redundant (color and sound) trials (2 trials per SOA of -200, 0, 200 ms)[3]. After each trial of the warm-up (but not the experimental blocks), a feedback about the correctness of the participant's response was presented on the screen, responses of the familiarization block were not recorded. Each experimental block contained 28 no-go trials, 28 color trials, 28 sound trials and 28 redundant (color and sound) trials. Observers had the opportunity to take a break in the middle of the block; observers were informed about this by a display appearing at each mid-block. A total of 784 recorded trials were presented, with trial types appearing in randomized order.

4.4.2. Results and discussion

The results are reported in two parts, mean RT analyses conducted to determine whether there are redundancy time gains and analyses of the violations of Miller’s (1982) RMI to determine which class of processing model best fits the observed data. To avoid confounds by anticipatory and extremely slow responses, reaction times below 200 ms and above 1200 ms were excluded from analysis (1200 ms limit was chosen in function of the overall RT distributions). Extreme RTs, namely reaction times exceeding 2.5 standard deviations of the mean of each single feature condition and each SOA were also excluded, individually for each observer. By these criteria, 2.3 % and 1.6 %, respectively of trials were excluded. Miss and false alarms rates were below 5 %, on average. Two participants were excluded from analyses because of too high an overall error rate (12.25 % and 37.87 %, respectively), one further participant was excluded due to restricted monocular vision.

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[3] Larger SOAs for redundant targets were used in the warm-up block (than in the experimental blocks) to stress the possible time interval between feature changes.

Mean RTs and redundancy gains. The mean RTs are presented in Table 4.2 and Figure 4.4**.** A repeated-measure ANOVA with the factor trial type (sound, color, redundant) showed a significant main effect of trial type (*F*(2,22) = 20.87, MS$_e$ = 378.3, *p* < .001); multiple comparisons to follow-up the main effect indicated that redundant change trials (great mean = 319.9 ms, *SD* = 33.5 ms) were processed significantly faster than sound (*M* = 365.0 ms, *SD* = 55.4 ms; *t*(11) = 5.35, *p* < .001) and color trials (*M* = 363.7 ms, *SD* = 44.2 ms; *t*(11) = 8.49, *p* < .001). RTs of sound vs. color trials did not differ significantly (*t*(11) = .14, *p* > .10).

Table 4.2

Mean correct Reaction Times (RT) for target types of detection task in the visuo-auditory paradigm (the error rates are computed in function of the number of trials per condition).

Target type		RT (ms)		Error rates (%) Miss		Extremes		Mean RT (ms) redundancy gains GainB&C		GainM&L		GainAvg	
Single defined targets													
Sound		364.98	(55.40)	0.09	(0.08)	2.71	(0.89)						
Color		363.67	(44.15)	0.02	(0.07)	1.91	(1.11)						
Redundant defined targets													
	-60ms	322.80	(36.46)	0.00	(0)	0.12	(0.07)	42.18	(29.72)	31.01	(27.59)	41.53	(22.91)
	-40ms	314.36	(31.12)	0.00	(0)	0.05	(0.09)	50.63	(31.86)	39.45	(22.80)	49.97	(21.29)
	-20ms	306.03	(34.07)	0.00	(0)	0.08	(0.07)	58.96	(26.25)	47.78	(21.63)	58.30	(18.18)
FCA	0ms	311.73	(35.37)	0.00	(0)	0.11	(0.07)	53.25	(32.11)	42.08	(25.86)	52.60	(21.16)
	20ms	315.11	(34.88)	0.00	(0)	0.08	(0.07)	49.88	(33.88)	38.70	(19.78)	49.22	(21.16)
	40ms	325.21	(37.18)	0.00	(0)	0.08	(0.07)	39.78	(31.61)	28.60	(20.76)	39.12	(18.76)
	60ms	344.17	(41.02)	0.00	(0)	0.06	(0.07)	20.81	(36.66)	9.63	(25.42)	20.15	(27.72)
	M	319.92	(33.46)	0.00	(0)	0.08	(0.07)	45.07	(29.16)	33.89	(19.75)	44.41	(17.60)

Note. Mean RT redundancy gains are relative to the fastest single-feature (Gain$_{B\&C}$ and Gain$_{M\&L}$) and relative to the average of both single feature targets (Gain$_{Avg}$). $_{B\&C}$ = Biederman and Checkosky (1970). $_{M\&L}$ = Miller and Lopes 1988).

A one-way repeated-measures ANOVA of redundant target change RTs with the factor SOA showed a significant main effect of SOA (*F*(6,66) = 9.75, MS$_e$ = 192.53, *p* < .001); there was a quadratic effect (*F*(1,11 = 29.24, MS$_e$ = 246.35, *p* < .001). Multiple comparisons did not reveal significant differences between adjacent SOAs (all *t*(11) < 2.67, *p* < .10). Further, the fastest RTs occurred at an SOA of -20 ms, but no significant difference was observed between both SOAs of 0 and -20 ms. Finally, a significant linear effect was also observed (*F*(1,11) = 13.30, MS$_e$ = 290.12, *p* < .01), explained by the RT asymmetry between SOA -60 and +60 (Table 4.2).

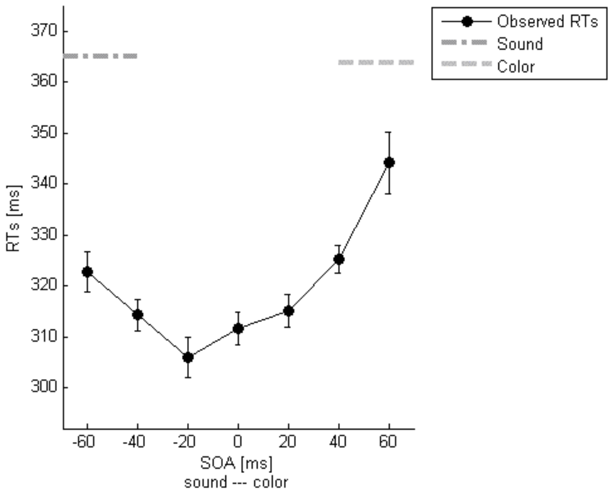

Figure 4.4. Mean RTs (ms) as a function of SOA. The solid line represents the mean RT (and standard error) for the correct redundant trials for each SOA. Dashed lines at each side of the graphic indicate the mean reaction time for the Color and Sound conditions.

RTs to redundant targets were 44.4 ms faster than average RTs for single color and sound changes (Gain_{Avg}). Testing redundancy gains ($\text{Gain}_{\text{B\&C}}$) under the *fixed-favored feature* assumption reveals a 45.1 ms redundancy gain, while testing under the assumption of variable feature preference ($\text{Gain}_{\text{M\&L}}$) shows a redundancy gain of 33.9 ms. The right-hand part of the Table 4.2 shows the redundancy gains for each SOA using the three procedures. A repeated-measures ANOVA of redundancy gains showed the same results as the ANOVA of RTs: the main effect of SOA was significant ($F(6,66) = 9.75$, $MS_e = 192.53$, $p < .001$) and accompanied by a significant quadratic effect (F(1,11 = 29.24, $MS_e = 246.35$, $p < .001$). To test whether the redundancy gains differed from 0, a one-sample t-test was applied to the redundancy gain values obtained by applying the Miller and Lopes (1988) procedure. Only redundancy gains with SOA +60 were not statistically different from 0 (see Table 4.3).

*Physiological synchronicity***.** Diederich and Colonius (2004) proposed a procedure to determine the facilitatory effect for redundant targets based on a method used by Meredith and Stein (1986) to investigate the multisensory response enhancement (MRE) or inhibition of neurons in the colliculus superior. The facilitatory effect (or MRE, respectively) is computed according to:

$$MRE = \frac{\min(\overline{RT}_A, \overline{RT}_V) - \overline{RT}_{A\tau V}}{\min(\overline{RT}_A, \overline{RT}_V)} \times 100,$$

in which $\overline{RT}_A$ corresponds to the mean reaction time for single auditory stimuli, $\overline{RT}_V$ to the mean RT for single visual stimuli and $\overline{RT}_{AV}$ to the mean reaction time for a visuo-auditory target. τ represents the time interval between auditory and visual stimuli (SOA). As an example, a MRE with a value of 10 indicates that a redundantly defined target at a particular SOA is detected 10% faster than the faster of the singly defined targets (i.e., its processing time is 10% shorter). According to Raab's (1962) "physiological synchronicity" model, the largest facilitation should is predicted to be observed at the SOA closest to the difference between the mean RTs of the two singly defined targets; this difference reflects the supposed maximal overlap of the tow RT density distributions. Consequently, the maximum MRE would be expected close to the difference between single feature mean RTs (Diederich & Colonius, 2004). As shown in Figure 4.5, the maximal observed MRE did not coincide with the predicted MRE, suggesting that the processing of visuo-auditory stimuli cannot be accounted for by a model assuming physiological synchronicity.

Table 4.3

One sample t-tests for the redundancy gains computed using Miller-Lopes (1986) method for all SOAs and their mean (* two-tailed).

		t(11)	sign*
FCA	*-60ms*	3.89	0.003 **
	-40ms	5.99	0.000 ***
	-20ms	7.65	0.000 ***
	0ms	5.64	0.000 ***
	20ms	6.78	0.000 ***
	40ms	4.77	0.001 ***
	60ms	1.31	0.216
	Mean	5.94	0.000 ***

RT distributions analyses. Miller (1986) proposed an extension of Miller's (1982) RMI taking SOA between stimulus onsets into account: $F_R(t) \leq F_{T1}(t-SOA_{T1})+ F_{T2}(t-SOA_{T2})$, in which SOA_{T1} represents the time between the display onset and the first stimulus onset, whereas SOA_{T2} corresponds to the time elapsed between the display onset and second stimulus onset. Because the onset of one of these stimuli corresponds to measurement onset, the SOA for this stimulus is set to 0. Applying the Miller (1986) inequality to the present data revealed that parallel-coactive processing occurred only if the visual stimuli did not change after the auditory stimulus (see Figure 4.6). A maximum number of nine RMI violations were observed at SOAs of 0 and +20, whereas at SOA +40 eight violations and at SOA +60 only one violation was observed. This result suggests that parallel coactive processing of visuo-auditory stimuli takes place in the time window of 0 to 40 ms, but only when the visual stimuli changes first.

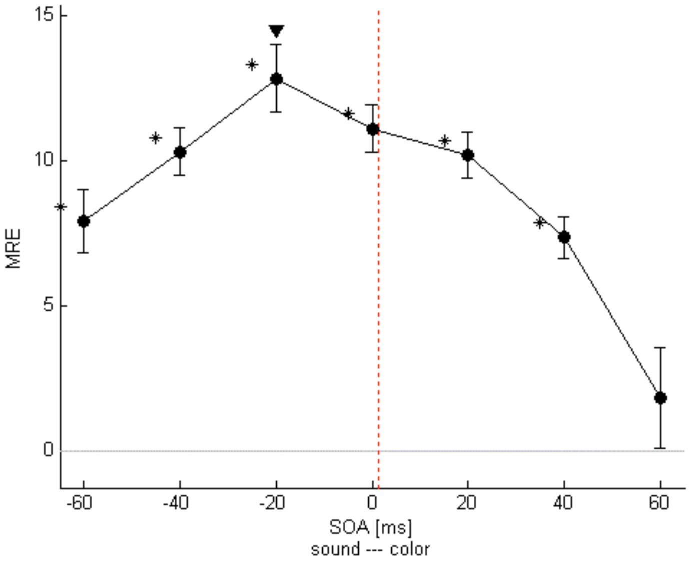

Figure 4.5. Multimodal response enhancement (MRE) as a function of the SOA. The black line corresponds to the MRE for each SOA. The triangle indicates the maximal observed MRE whereas the vertical dashed line indicated the predicted MRE. Stars indicated that MRE was significantly greater than 0.

To sum up, results of mean RTs, redundancy gain and distribution analyses revealed that visuo-auditory stimuli are most efficiently integrated in cross-modality search when visual stimuli change in a range between 0 to 40 ms before auditory stimuli. This finding is consistent with studies on simultaneity perception (Slutsky & Recanzone, 2001; Spence et al., 2003; Stone et al. 2001, Zampini et al., 2003, 2005) in which perception of simultaneity of visual and auditory stimuli was found when visual stimuli preceded auditory stimuli between 0 and 80 ms. Further, the finding of a time window of 0 to 80 ms is in agreement with results obtained in asynchronous visuo-auditory onset detection (Diederich & Colonius, 2004). The observations are also coherent with neurophysiologic recordings demonstrating that auditory signals reach multimodal cortical brain regions around 30 ms earlier than visual signals (Molholm et al., 2006).

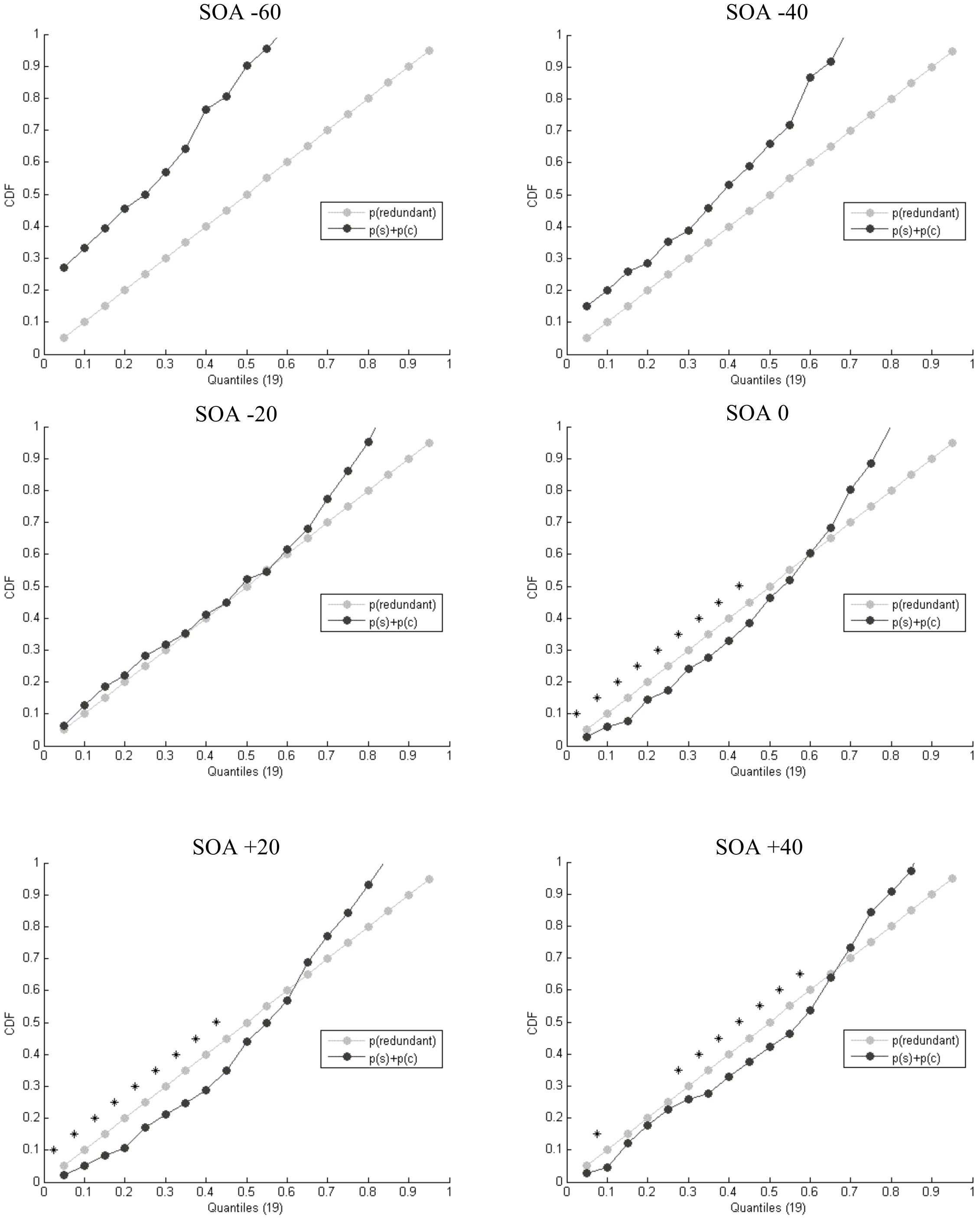

Figure 4.6. Results of the tests for violations of Miller’s (1986) RMI in RTs of Experiment 2 according to the SOA. The dark grey curve represents the cumulative probability function for the summed probabilities of RTs to single targets having occurred at a given time t; the light grey curve represents corresponding redundant target probabilities. Significant violations are marked with a star ($p < .05$). Note that for the RMI to be satisfied, summed single dimension probabilities must be no smaller than redundant target probabilities.

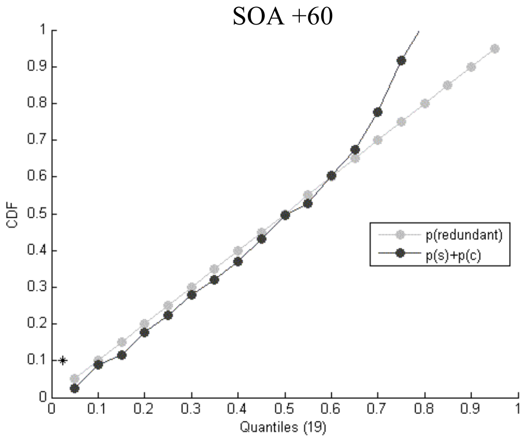

Figure 4.6 (Continued).

4.5. General discussion

Multisensory redundant color and sound targets in Experiments 1 and 2 of the present study generated redundancy gains, a first sign of a multisensory integration in search tasks. Violations of Miller's (1982) race model inequality in Experiment 1 provided clear evidence that cross-modal features are integrated in a parallel coactive processing architecture in a tasks involving selective processing; replication a finding that was already observed in onset detection tasks (e.g., Arndt & Colonius, 2003; Colonius & Arndt, 2001; Diederich & Colonius, 2004; Forster et al., 2002; Hughes et al., 1994; Miller, 1982, 1986; Patching & Quinlan, 2004). Experiment 2 confirmed results in the literature (Diederich & Colonius, 2004; Molholm et al., 2006; Slutsky & Recanzone, 2001; Spence et al., 2003; Stone et al. 2001, Zampini et al., 2003, 2005) of an integration window showing an optimal feature integration when visual stimuli changed from between 0 to 40 ms before auditory stimuli. In association with the results obtained in visual search tasks (Krummenacher et al., 2001, 2002a, b; Schönwälder, 2006), these findings suggest therefore that similar processes underlie feature integration within and between sensory modalities, giving support to the idea of a supra-modal integration system (Macaluso & Driver, 2005).

Further evidence of a supra-modal organization of the perceptual system can be found in studies investigating cross-modal attention shifts. A cue presented in one modality can influence the detection speed of the position of a target displayed in another modality (Butter, Butchel & Santucci, 1989; McDonald, Teder-Sälerjärvi & Hillyard, 2000; McDonald & Ward, 2000; Spence & Driver, 1997; Ward, 1994). Additional support to this hypothesis is found in electrophysiological studies, demonstrating that the validity of a symbolic cue presented in one modality affected brain activity for a target displayed in another modality (e.g., Eimer, Cockburn, Smedley & Driver, 2001; Eimer & Schröger, 1998; Eimer, van Velsen & Driver, 2002). Finally, neuroimaging studies observed that visual and cross-modal attention shift tasks activated common brain areas (e.g., Downar, Crawley, Mikulis & Davis, 2000; Macaluso, Frith & Driver 2002; Macaluso, Eimer, Frith & Driver, 2003; Shomstein & Yantis, 2004).

Although several sub-cortical and cortical brain areas are activated when multimodal stimuli are presented, one possible neural location for the multimodal integration is the colliculus superior. The deeper layers of this midbrain structure receive projections from cortical areas involved in visual, auditory and somatosensory information processing (Lund, 1972). In single cell studies, Meredith, Stein and colleagues observed an enhanced response in cells of the colliculus superior to multimodal stimuli compared to unimodal stimuli (Meredith & Stein, 1986; Wallace, Meredith & Stein, 1998). Further, the benefit for multisensory stimuli is affected by the distance separating stimulus sources, namely when the stimuli were not presented within the same receptive field of the colliculus superior cells (Kadunce, Vaughan, Wallace & Stein, 2001). In addition, collicular response is sensitive to the timing of stimulus presentation; the larger the time interval between stimuli, the weaker the response (Meredith, Nemitz & Stein, 1987). Finally, lesions of this structure provoke a loss of multisensory orienting behavior (Burnett, Stein, Perrault & Wallace, 2007). The colliculus superior seems therefore to be a suitable candidate for the multisensory integration location.

Results of the present Experiments 1 and 2 permit an evaluation of the resources allocated in multimodal search tasks. First, it was shown in Experiment 1 that detecting the color change of a unique bar was significantly faster than detecting the auditory change, whereas, when the whole display changed in Experiment 2, detection time for visual and auditory stimuli were similar. This suggests that a global change in the visual scene is detected easier than a local change. Such a finding is coherent with Navon’s (1977) classic results. Navon used large character (global level) stimuli made out of small characters (local level), and participants had to identify either the global or the local character. Navon found an overall faster identification of a global than a local character (global precedence effect). However, the present Experiment 1 provided hints that search tasks using multimodal stimuli might not be ruled by the global precedence principle. Single global auditory changes were significantly slower than single local visual changes. This imbalance on the detection level seems to force the information processing system to prioritize visual stimuli, whose changes were more easily detectable than for those of the single auditory stimulus. This leads to faster detection of visual compared to auditory changes. This assumption finds support in studies observing a performance drop in a peripheral detection task when participants had to follow a telephonic conversation in comparison to detection performance without a supplementary task (Patten, Kircher, Östlund & Nilsson, 2004). Moreover, this forced biased resource allocation may slow down the whole feature processing, as shown by a detection time increase of 50 ms for single auditory and redundant changes in Experiment 1. Further research investigating local visuo-auditory detection is needed to confirm these assumptions.

5. Oculomotor parameters during visual search for single and dual redundant targets: support for a spatial saliency-based control mechanism of eye movements

5.1. Abstract

The present paper was aimed at testing whether the control of the oculomotor system relies on a mechanism based on spatial summation of saliency signals as was proposed for the orientation of attention by Guided Search (e.g., Wolfe, 1994). Observers' oculomotor behavior was first investigated with two visual search tasks requiring the according features to be processed differently deep (Experiment 1). In the first task (detection task), observers had to react to the presence of any (singly or redundantly defined) odd item in the search display. According to the idea of spatial saliency signal summation, a redundantly defined signal should generate a larger saliency signal than a singly defined one. Results confirmed this expectation by demonstrating that saccades were faster elicited in trials with redundant compared to trials with single targets. However, in the second task (conjunction search), when the exact feature combinations of the target had to be identified, saccade latencies were even shorter than in the detection task. Altogether, these results provided support for a spatial saliency-based guidance of the oculomotor system that could be seen as the 'default' control mode. However, these settings can be modulated when additional task requirements are imposed as was shown in Experiment 2. Only a spatial overlap of both target defining features in the redundant condition (i.e., a single rather two separate target items) expedited saccadic latencies. When both features were physically separated, this advantage for redundant targets was abolished.

5.2. Introduction

Which kinds of relationship have attentional and oculomotor systems? In a natural context one might argue that attention is where eyes are looking at. When looking for a friend in a crowd, it is pretty impossible to see her or him without moving the eyes. Laboratory settings (Posner, Nissen & Ogden, 1978; Posner, Snyder & Davidson, 1980) and people suffering from progressive supranuclear palsy (Rafal et al., 1988) have demonstrated that without degrading performances attention can move although eyes remain fixed, or eyes move although attention remains fixed (Stelmach, Campsall, & Herdman, 1997). Nevertheless, other studies found close links between oculomotor and attentional systems. Hoffman and Subramaniam (1995) showed a facilitation effect when attentional focus coincide with saccade destination location, whereas Deubel and Schneider (1996) observed that attention is located where a saccade is planned to land.

Neurophysiologic studies (Beauchamp, Petit, Ellmore, Ingeholm & Haxby, 2001; Corbetta et al., 1998; Nobre, Gitelman, Dias & Mesulam, 2000) demonstrated that attentional and oculomotor systems share a common functional neuronal network consisting of intraparietal, postcentral and precentral sulci. Single cell studies showed that the posterior parietal cortex (Bushnell, Goldberg & Robinson, 1981), the frontal eye field (Thompson, Biscoe & Sato, 2005), the colliculus superior (Kustov & Robinson, 1996) and the pulvinar (Petersen, Robinson & Keys, 1991; Peterson, Robinson & Morris, 1987) were also activated during attentional and ocular shifts.

Visual search literature provides additional evidence for a link between attention and eye movements. Despite a lack of agreement (Klein & Farell, 1989; Maioli, Benaglio, Siri, Sosta & Cappa, 2001), precluding eye movements seem to degrade behavioral performance during tasks in which the target object differs from the non-target objects by its unique combination of attributes (e.g., a red horizontal bar among green, horizontal and red, vertical bars) (Scialfa & Joffe, 1998). This type of search was referred as feature conjunction search task (e.g., Treisman & Gelade, 1980), in comparison to a feature detection search task, in which the target differs from non-target objects in one (or more) feature (i.e., a red vertical bar among green vertical bars). Furthermore, the distinction between feature detection and conjunction searches observed in manual responses (i.e., a RT increase proportional to the number of displayed items only in conjunction search tasks) is found in oculomotor parameters as well (Williams, Reingold, Moscovitsch & Behrmann, 1997; Zelinsky & Sheinberg, 1997).

Moreover, the number of fixation increases with object complexity (Locher & Nodine, 1978).

5.2.1. A common control mechanism for attentional and oculomotor guidance?

The fact that attentional and oculomotor systems seem to be functionally linked suggests a possible common, or at least similar, mechanism for controlling shifts of attentional and ocular foci. Some studies (Findlay & Walker, 1999; Findlay & Gilchrist, 1998; Shen, Reingold & Pomplum, 2000) proposed a model formalized by Itti and Koch (2000) in which ocular shifts coincide with the most salient (visible) object in the visual field. This assumption is derived from early versions of the attention orienting model in visual search called Guided Search model (Wolfe, Cave, & Franzel, 1989; Wolfe, 1994). This model postulates that basic features are extracted simultaneously and in parallel by dimension-specific modules (such as color, orientation, etc.) to form a representation of the visual scene. After feature extraction, each module generates a so-called saliency signal represented in a saliency map that contains a dimension-specific contrast signal for each location of the visual scene. This saliency signal reflects the strength of the local difference between one object and its neighbors for a particular dimension. The larger the local difference, the stronger the saliency signal at this location. The saliency maps are finally summed onto an overall dimensional saliency map, in which only the strength and position of the saliency signals are represented. Finally, focal attention is guided toward the object presenting the larger saliency signal. The saccadic saliency map adopts the same mechanisms as the Guide Search model, namely the saccade guidance toward the most salient object in visual field.

5.2.2. Redundancy and eye movements

One way to test this kind of models can be found in varying the target saliency. This latter can be diminished if the target is surrounded by heterogeneous distractors sharing some of its features (e.g., a red horizontal bar among red vertical and green horizontal bars) or amplified by over-defining the target (e.g., a red horizontal bar among green vertical bars). Krummenacher, Müller and Heller (2001, 2002a, b) found that redundantly (over-) defined targets are faster detected than singly defined targets (e.g., a red vertical bar among green vertical bars), demonstrating that the relative saliency strength between the target and distractors plays a major role in, at least, attention orienting. The use of both redundantly and singly defined targets allowed them differentiating between two different processing models. Both assume that feature signals are processed independently and in parallel, but diverge concerning the mechanisms that generate the response associated to the target detection. A first model postulates that redundancy gains, referring to the faster detection of redundantly defined targets (compared to singly defined targets), result from a parallel race of independent signals, whose winner triggers the response (race model; Raab, 1962), whereas an alternative account assumes that both features contribute to the response triggering (parallel co-active model; Miller, 1982). Miller demonstrated that all models postulating a strict parallel processing between features, as the race model (Raab, 1962), do not violate the race model inequality. Consequently, a violation of this inequality speaks in favor of a parallel co-active processing of features.

Although redundancy is only few investigated in terms of oculomotor parameters, some studies based on the detection of a multisensory signal (Arndt & Colonius, 2003; Colonius & Arndt, 2001; Engelken & Stevens, 1989; Hughes et al., 1994) observed shorter saccadic latencies for redundantly (visuo-auditory) defined targets than for singly defined (either visual, or auditory) targets. RMI violations were also recorded (Arndt & Colonius, 2003; Hughes et al., 1994). One recent study, (Turatto & Betta, 2006) measured saccadic latencies under redundancy conditions. Observers' task was to execute a saccade from the fixation point to the target point (5° above fixation point) when a visual signal occurred. This signal consisted of one or two disks appearing either at the same level of (Experiment 1) or below the fixation point (Experiment 2). The two disks condition generated smaller saccade latencies and RMI violations (at least in Experiment 1). The fact that redundant signals can influence oculomotor parameters (at least reduce saccadic RTs) reinforce subsequently the hypothesis of a saccade guidance based on saliency.

5.3. Experiment 1

The aim of Experiment 1 is to examine the strength of the link between eye movements and attention by manipulating task difficulty. Previous studies (Williams et al., 1997; Zelinsky & Sheinberg, 1997) showed that modifying the display characteristics (bottom-up influence) modulates the number of eye movements used to solve the task, namely more eye movements are required when the search display becomes heterogeneous (conjunction search task). Another way to manipulate difficulty is to vary task requirements (top-down influence). In Experiment 1, identical displays (namely, redundantly defined targets) are presented in two consecutive sessions, but tasks requirements changes. Observers' goal for the first session was to press a key only when a (singly or redundantly defined) target was displayed among distractors (detection task), whereas observers have to react only at predefined redundantly defined targets in the second session (conjunction task).

In addition, using redundant targets permits to investigate the sensitivity of oculomotor parameters to saliency manipulation in a detection task. If the oculomotor system is purely driven by bottom-up signals, saccadic RTs should diminish for redundantly defined targets in comparison to singly defined targets. Furthermore, if guidance by saliency is the unique mode for the control of eye movements, oculomotor parameters for redundant targets should not be affected by task type (detection vs. conjunction task), because both of them used a physically identical search display. This argument is however hardly tenable. Indeed, observers are able to voluntary monitor their eye movements, as showed in the anti-saccade paradigm (e.g., Hallett, 1978), suggesting that guidance by saliency can be envisaged as a "default mode" that can be overruled in function of the task requirements.

5.3.1. Method

Observers. Thirteen observers (nine female and four male) took part in Experiment 1. All observers were students at the University of Fribourg. They received course credits or were paid at a rate of CHF 5 per hour. Observers age ranged between 20 and 29 year (median = 25). All of the observers were right-handed. All of the observers had a normal or a corrected-to-normal vision, including color vision.

General design. Experiment 1 comprised of two conditions, the detection and conjunction tasks. Each of the conditions was administered in one session that took about 20 minutes to complete, both sessions being run consecutively. Observers started systematically with the detection task. Instructions were both displayed on the monitor and presented orally, by the instructor at the beginning of each session. Observers were told that they could ignore the eye-tracking device. Responding was by pressing the space bar in go trials, in no-go trials, observers were instructed to refrain from any response.

Stimuli. In both sessions, visual stimuli, in target-absent trials, were 49 green vertical bars, each subtending .88° x .2° of visual angle presented on a grey background (RGB: 87, 87, 87). Colors were roughly isoluminant (RGB green: 0, 200, 0). Bars were displayed in the cells of a virtual matrix of 7x7 rows and columns. The entire display subtended an area of 16.18° x 16.18° of visual angle. The position of each display item was randomly jittered relative to the cell center with jitter ranging between a minimum of 0° and a maximum of ±0.5° both along the horizontal and vertical axes. The minimum (maximum) distance between centers of gravity of neighboring items was 1.71° (3.71°) horizontally and vertically.

In the detection task, in no-go (target-absent) trials, all search items were green vertical bars. In go (target-present) trials, one of the green bars was replaced by a target item that could differ from distractors in either one dimension (color or orientation; single-target trials), or in both dimensions (color and orientation; redundant trials). In orientation trials, the target was a green bar tilted 45° to the left or right; in color trials, the target was a vertical bar, colored red (RGB: 255, 0, 0) or blue (RGB: 0, 0, 255). In redundant trials, the target item was colored red or blue, and tilted to the left or right (red-left; red-right; blue-left; blue-right).

In the conjunction task, a target differing from distractors (identical as those used in detection task) on both the color and the orientation dimensions was present in all experimental trials. Observers were instructed to respond only if the target was defined by either of two pre-defined combinations of features (e.g., respond if the odd item is red and left-tilted or blue and right-tilted; do not respond if the odd item is red and right-tilted or blue and left-tilted). Feature combinations were assigned to observers randomly. A part of them had to react only if the odd item was either red and left-tilted or blue and right-tilted, whereas the second part hat to respond only if the odd item was either red and right-tilted, or blue and right-tilted

Procedure. In the detection task observers completed one short warm-up block of 16 trials, comprised of four no-go and 12 go trials (four color, orientation, and redundant trials, respectively). The experimental session involved five blocks of 48 trials each. Of the 48 trials, 12 trials of each trial type (absent, color, orientation, redundant) were presented.

Observers were instructed to respond as quickly as possible if one of the bars differed from the other bars by depressing the space bar of the keyboard with the index or middle finger of their dominant hand. Instructions were presented on the screen, at the beginning of the warm-up block and observers were instructed orally by the investigator.

Each trial began with the presentation, for 500 ms, of a fixation cross indicating the center of the monitor, fixation was followed by a blank (grey) screen for 500 ms. The search display was presented for a maximum of 1500 ms or until the space bar was depressed by the observer. The display was followed by an inter-trial interval (a grey, blank screen) of 700 ms. In the initial exercise/familiarization block, visual feedback indicating whether the response of the previous trial was correct or not, was presented for 800 ms following the response.

In the conjunction task, observers completed one warm-up block of 16 trials (four of each combination of features; i.e., target-type). The experimental session consisted of four blocks of 40 trials, ten trials for each of the four feature combinations (red-left, red-right, blue-left, blue-right). The sequence of events in a trial was the same as in the detection task.

Apparatus. Observers were seated, in a darkened room with a deem background illumination, in front of a cathode ray tube (CRT) monitor with a screen diagonal of 17", run at spatial resolution of 1024 x 786 pixels and a refresh rate of 60 Hz driven by a Hewlett Packard PC under the Windows XP operating system. Observers were seated at an approximate distance of 57 cm from the monitor with distance maintained by use of a chin and forehead rest. Stimulus presentation and data collection was controlled by a MatLab script and the Psychophysics and EyeLink Toolbox extensions (Brainard, 1997; Pelli, 1997; Cornelissen, Peters & Palmer, 2002; see http://psychtoolbox.org/). Eye movements were recorded with a 250 Hz sample rate (i.e., a sample was taken every four ms) with an SMI EyeLink I system (SR Research Ltd., Version 2.11). Head position was held constant with a chinrest the vertical position of which was adjustable and a forehead rest that served as physical reference informing the observer that head and forehead were in the correct (instructed) position. The eye tracker was calibrated using the nine-point calibration procedure provided by the manufacturer at the beginning of each experimental session. In order to maintain accuracy of the eye movement signal during the entire experimental session, a drift correction was performed at the beginning and the middle of each block.

Data analysis. The same analysis procedures were applied to manual and oculomotor data of the detection and conjunction conditions. Manual RTs of trials with incorrect responses, together with anticipatory (RTs faster than 200 ms) and exceedingly slow reaction times (detection task: 1200 ms; conjunction task: 1600 ms) were discarded from analysis[4]. In addition, RTs exceeding ±3 standard deviations of the mean were excluded from analysis,

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[4] Note that the limits for anticipatory and slow responses were chosen with regard the overall RT distributions.

individually for each observer and each dimension. Applying these procedures resulted in rejection of a total of 3.3 % of trials in the detection condition and 3.65 % of trials in the conjunction condition. The data sets of observers whose overall error rates exceeded 10% were also discarded from analysis (by the criterion, one participant of the conjunction condition was excluded from analysis).

The eye movement data of all experimental trials were inspected visually and classified into one of four trial categories. Category 1: No eye movement occurs while the search display is visible or after display has disappeared[5]; category 2: eye movements (at least one saccade and one fixation) are made during the presentation of the search display; category 3: a saccade is initiated while the search display is visible; and category 4: eye movements occur only after the search display has been erased. For some of the analyses, only two categories were used: category 2 and the merged data of categories 1, 3 and 4.

For category 2 (eye movements during the search display) trials with saccades that were not directed toward the target location, were discarded because it must remain unclear why they were directed at that particular (non-target) location (a total of 9.3% of all trials were discarded from analysis on the location criterion).

Five eye movement parameters were computed for trials presenting eye movements: 1) number of saccades, and, related, 2) number of fixations observed during the time the search display was visible, 3) latency of the first saccade (i.e., the delay between display onset and the beginning of the first saccade), 4) the distance error of the first fixation (i.e., the distance between the landing point of the first saccade and the center of gravity of the target item), and 5) "inspection time". Inspection time is defined as the ratio between the time elapsed since the onset of the search display and the point in time at which the last saccade that is generated while the search display is visible ends and the manual RT. This index allows disentangling the proportion of the RT devoted to "physically" find the target from the time required for the selection and execution the appropriate manual response. Because this index assumes implicitly a direct link between RTs and eye movements, it was reported as peripheral information. Note that, in order to avoid including express saccades (i.e., saccades with extremely short latencies [Fischer et al., 1993]), trials with saccade latencies faster than 50 ms were excluded from analysis. Finally, to draw valid conclusions about oculomotor parameters,

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[5] Eye movements occurring after the display had disappeared were introduced to take account of saccades made after the manual response had been executed.

observers with fewer than ten valid trials in at least one of the search conditions (detection, conjunctions search) were excluded from analysis.

5.3.2. Results

5.3.2.1. Detection task

The data of the detection task are analyzed in two subsections; the first section is dedicated to manual RTs and oculomotor parameters, the second compares RTs of trials with and without eye movements.

Behavioral data

Error rates. Error rates in the detection task were low overall with miss rates of .0 % (i.e., no target item was missed at all) and an average false alarm rate of 5.6 % (*SD* = 1.4%).

Manual RTs. RT data are reported in two parts, mean RTs and mean RT redundancy gains and analyses of the entire RT distributions and tests for violations of Miller's (1982) race model inequality (RMI) to establish the underlying processing architecture (parallel race model vs. parallel co-active processing).

A one-factor repeated-measures ANOVA of the mean RTs with the factor target definition (color, orientation, redundant) showed a significant effect of the target definition ($F(1.34,16.10) = 23.05$, $MS_e = 302.09$, $p < .001$; Huynh-Feldt-corrected degrees of freedom). Redundant (*M* = 388.6 ms, *SD* = 72.7 ms) and color targets (*M* = 395.0 ms, *SD* = 83.6 ms) were significantly faster detected than orientation targets (*M* = 424.4 ms, *SD* = 70.2 ms, see Table 5.1). Redundant targets are globally detected 21.4 ms faster than the average of single targets ($t(12) = 9.11$, $p < .001$). The result that mean overall RTs to color targets are faster than to orientation trials might suggest that all the observers' RTs to color targets are faster, i.e., that there is a fixed-favored feature or dimension (see Biederman & Checkosky, 1970). If redundancy gains are tested under the fixed-favored dimension assumption, a significant ($t(12) = 4.65$, $p < .001$) gain of 24.8 ms for redundant compared to color targets is observed. The fixed-favored feature assumption, however, is not necessarily correct, as observers might prefer different dimensions or dimension at all. Miller and Lopes (1988) suggested that over-or under-estimations of mean RT redundancy gains can be avoided by application of the following test procedure. Mean RTs to the single targets are compared individually for each observer. If RTs differ significantly (using a liberal criterion of $\alpha = .10$), the faster single dimension RT is used for comparison with redundant target RTs, if RTs do not differ, the mean RT of the two single dimension target types is used for comparison. Calculation of mean RT redundancy gains according to the Miller et al. (1988) procedure results in a marginally significant overall redundancy gain of 4.7 ms ($t(12) = 1.60$, $p = .07$; testing was one-tailed because of the studies by Krummenacher et al. [2001, 2002a, b] reported redundancy gains in a singleton feature detection task involving the color and orientation dimensions).

Distribution analysis. For the analysis of the distributions, observers with less than thirty valid trials in any one of the three target-present conditions were excluded from the analysis (by this criterion none of the observers was excluded). As mentioned above, Miller's (1982) test for violations of the RMI allow differentiating a parallel co-active model (e.g., Miller, 1982) from a strict parallel model, as race model (Raab, 1962). Miller (1982) proved that all models postulating a strict parallel processing between features do not violate the following inequality: $F_R(t) \leq F_{T1}(t)+ F_{T2}(t)$, where t is the time since display onset and F the cumulative function of the RTs. T1 and T2 correspond to features composing the redundantly defined object R. This inequality is violated when, at a certain time *t*, the probability to trigger a response for a redundant (color & orientation) target is larger than the summed probability to trigger a response for a target defined by color or orientation (singleton feature target). In order to compare observers, RT distributions are expressed in quantiles (i.e. the 5th, 10th, etc., percentiles). Because Krummenacher et al. (2001, 2002a, b) demonstrated evidence for parallel co-active architecture underlying processing of dimensional signals in visual search for singleton feature targets, cumulative probability functions for redundant targets and summed probability functions of single targets at each quantile are compared using one-tailed t-tests.

The tests revealed no significant violations of the RMI in the analysis of the entire set of observers, (see Figure 5.1), six observers (out of thirteen) showed a smaller (summed) probability of having responded to single targets at time t than to redundant targets. That is, these observers showed violations of the RMI, a result indicating the parallel co-active processing is the adequate underlying processing architecture. In detail, the proportion of detected redundant targets relative to the summed proportion of detected single targets was violated in the 4 quantiles. As violations of the RMI are observed, parallel race model architectures can be excluded. This finding replicates the results of Krummenacher et al. (2001, 2002a, b) who showed parallel-co-active processing in search for singleton feature targets.

Table 5.1

Mean correct target-present RTs and error rates (misses and extremes) for color, orientation and redundant targets in Experiment 1.

			Error Rates (%)			
Target type	RT (ms)		Misses		Extremes	
Color	395.69	(83.55)	0.00	(0)	1.92	(1.78)
Orientation	424.40	(70.20)	0.00	(0)	2.56	(2.11)
Redundant	388.61	(72.68)	0.00	(0)	2.05	(1.39)

Taken together, although the test for mean RT redundancy gains according to the procedure proposed to Miller and Lopes (1988) showed only a tendency of an advantage for redundantly defined targets and violations of the RMI were observed in a subset of observers only, results can be interpreted as evidence in favor of both faster processing of redundant targets and in terms of a parallel co-active processing architecture.

Oculomotor parameters

Eye movement parameters were analyzed based on the procedure described in the Method section. Table 5.2 shows proportions of trials of the five categories of trials in terms of eye movements a) trials without eye movements, b) rejected trials, c) eye movements while search display was visible, d) eye movements during and after search display was visible, e) eye movements after display had disappeared. As can be seen from Table 5.2, eye movement parameters are characterized by inter-individual variability resulting in large differences in proportions of trials that entered each category. In the detection task of Experiment 1, 6 out of 13 observers made eye movements in more than 50% of the trials (note that one participant [3] made eye movements toward distractor rather than the target location in about one third of trials with eye movements). Overall, eye movements were made in 56 % of trials. Confirming earlier findings by Zelinsky et al. (1997), this finding suggests that moving the eyes to the target is not required to efficiently perform feature detection tasks.

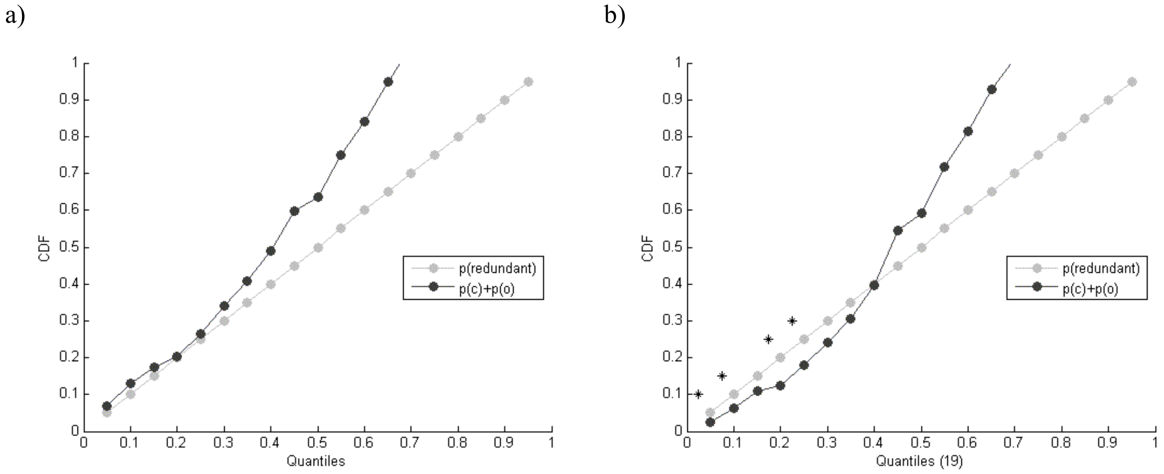

Figure 5.1. Results of the tests for violations of Miller's (1982) violation of the RMI in manual RTs in the detection task of Experiment 1; a) entire set of observers, b) subset of observers with violations of the RMI. The dark grey curve represents the cumulative probability function for the summed probabilities of RTs to single targets having occurred at a given time t; the light grey curve represents corresponding redundant target probabilities. Significant violations are marked with a star ($p < .05$). Note that for the RMI to be satisfied, summed single dimension probabilities must be no smaller than redundant target probabilities.

According to the criteria defined in the Method section, three of the observers with a too small number of trials with eye movements were excluded from analysis of the eye parameters. Separate one-factor repeated-measures ANOVAs with the factor target definition (color, orientation, redundant) were conducted to compare, in ten observers with at least ten valid trials in each condition, number of saccades, number of fixations, landing error of the first saccade and proportion of inspection time relative to manual RT. The ANOVAs showed no significant effect of target definition on the number of saccades ($F(2,18) = .48$, $MS_e = .004$, $p > .05$), the number of fixations ($F(2,18) = .38$, $p > .05$, $MS_e = .006$), landing error of the first saccade ($F(2,14) = 1.54$, $MS_e = 36.40$, $p > .05$) and proportion of inspection time ($F(2,18) = .91$, $MS_e = 6.29$, $p > .05$). Parameter means and standard deviations are given in Table 5.3. Note that, due to a temporary technical problem in recording the exact coordinates of the target, landing error for the first saccade could be computed for eight of the ten observers satisfying the minimum number of events criterion.

Interestingly, the latencies of the first saccade after display onset were significantly affected by the dimensional definition of the target ($F(1.30,11.68) = 48.10$, $MS_e = 101.17$, $p < .001$;

Huynh-Feldt-corrected degrees of freedom). Latencies of saccades to redundantly defined targets (*M* = 202.3 ms, *SD* = 20.0 ms) were significantly shorter than saccades to targets defined on the color (*M* = 210.6 ms, *SD* = 15.9 ms, *t(*9) = 4.88, *p* < .05) and orientation dimension (*M* = 236.4 ms, *SD* = 26.1 ms, *t(*9) = 5.66, *p* < .05).

Table 5.2

Trial proportions as a function of the categories a) No Events, Events during the display onset b) rejected, c) accepted, d) Events during and after the display, and e) Events after the display onset, separately for each participant in the detect task condition of Experiment 1

Observer	a)	b)	c)	Events	d)	e)
	No events	During display			During and after display	After display
		Rejected	*Accepted*	*Total*		
1	2.22	3.33	86.67	90.00	1.67	6.11
2	20.56	6.11	51.11	57.22	0.56	21.67
3	6.11	19.44	38.89	58.33	1.11	34.44
4	1.67	25.56	18.89	44.44	2.22	51.67
5	29.44	2.78	10.56	13.33	2.22	55.00
6	10.00	8.89	24.44	33.33	0.00	56.67
7	0.00	6.11	37.22	43.33	2.22	54.44
8	0.00	4.44	95.56	100.00	0.00	0.00
9	1.11	16.11	11.67	27.78	0.00	71.11
10	0.00	10.56	89.44	100.00	0.00	0.00
11	2.22	5.56	28.33	33.89	0.56	63.33
12	33.89	21.11	20.56	41.67	0.00	24.44
13	1.67	31.11	50.56	81.67	3.33	13.33
Mean	8.38	12.39	43.38	55.77	1.07	34.79

In trials with eye movements, one single saccade was sufficient to take the eye to the target, independently of its dimensional nature. However, the saccade was triggered earlier in trials with redundantly than with singly defined targets. Testing for saccade latency redundancy gains according to the Miller and Lopes (1988) procedure showed a significant a redundant gain of 9.7 ms (*SD* =5.5; *t*(9) = 5.79, *p* < .001).

Saccade latency distribution analysis. For the analysis of the entire RT distribution of first saccade latencies, observers with less than twenty valid trials per target dimension were excluded. The results of the distribution analysis reveal numerical violations of Miller's (1982) RMI, that is, summed probabilities of reactions to singly defined targets having occurred at time t smaller than the criterion probability of reactions to redundantly defined targets occurred at the time t. Violations of the RMI were statistically significant for the 5%

quantile (see Figure 5.2).

Table 5.3

Mean values (and standard deviations) of oculomotor parameters, separately for color, orientation and redundant targets of Experiment 1.

Target type	Fixation number	Saccade number	Saccade latency (ms)	Landing error (px)	Inspection time (%)
Color	1.08 (0.19)	1.07 (0.18)	210.61 (15.89)	41.51 (9.72)	67.44 (6.40)
Orientation	1.10 (0.10)	1.09 (0.08)	236.36 (26.06)	42.03 (11.64)	67.84 (6.21)
Redundant	1.08 (0.10)	1.06 (0.08)	202.27 (19.94)	37.20 (8.82)	66.37 (7.53)

The finding of violations of the RMI suggests that saccadic latencies are modulated by (multiple) dimensional signals in much the same way as behavioral RTs. Krummenacher et al., 2001, 2002a, b) in their interpretation of manual RT redundancy gains and violations of the RMI refer to models of visual search assuming that allocation of focal attention is controlled by saliency signals. One of the most important saliency-based models is Wolfe's (1994; Wolfe, Cave & Franzel, 1989) guided search (GS) model. GS assumes that saliency signals for a limited number of dimensions are generated and summed onto an overall saliency representation that controls the allocation of focal attention and gating of visual information to higher-order cognitive processes. Krummenacher et al. (2001) reasoned that targets defined (redundantly) on multiple dimensions would generate multiple saliency signals that would let the integrated saliency representation exceed a threshold limiting attention allocation faster than single signals. Mean RT redundancy gains argue in favor of parallel race architectures, violations of Miller's (1982) RMI provide evidence that dimensional signals are put into a consecutive processing module in a co-active fashion. Krummenacher et al. (2001, 2002a, b) found both mean RT redundancy gains and violations of the RMI. These results show that multi-dimensional signals controlling the allocation of focal attention are processed in a parallel co-active architecture.

The present findings of both (marginal) RT redundancy gains and violations of the RMI in latencies of saccades to dimensionally redundantly relative to singly defined targets suggests that the saliency signal that controls the generation of saccades operates on the same mechanism as the saliency signal that controls the allocation of focal attention. Findlay and Gilchrist (1998; Findlay & Walker, 1999) suggest that eye movements in visual search are controlled by a saliency representation. The present findings suggest that redundant dimensional information for behavioral responses and eye movements is processed by the same functional principle.

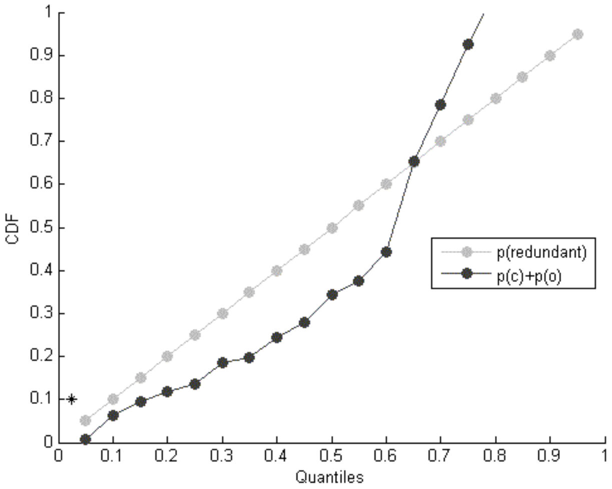

Figure 5.2. Results of tests for violations of the RMI (Miller, 1982) for the color and orientation (dark grey) and redundant (light grey) latencies of the first saccade after display onset.

Further, violations of the RMI on both, the manual and the oculomotor level, suggest that the integration of visual features occurs at an early, perceptual processing stage. This hypothesis was confirmed by Töllner, Zehetleitner, Krummenacher and Müller (in press) by means of an electrophysiological ERP (Event Related Potential) study. They examined whether redundancy gains arise at an early (feature selection, pre-attentive) processing stage as postulated by Krummenacher et al. (2001, 2002a) or at late (response selection, post-selective) stages following attentional target selection as claimed by Feintuch and Cohen (2002) or Miller, Beutinger and Ulrich (2009). Mental chronometry (RTs) was measured as well as electrophysiological ERPs reflecting either purely pre-attentive perceptual (PCN component [Posterior Contralateral Negativity]), post-selective, but still perceptual (stimulus-locked LRP [Lateralized Readiness Potential]), or purely response-related processes (response-locked LRP). As expected, redundancy gains and evidence for a parallel co-active processing were observed at a manual response level. Moreover, systematic modulation of the PCN latencies and amplitudes confirmed that redundancy gains originate from the feature processing stage. According to these results, integration of visual features occurs at an early stage of feature processing. Therefore, because the retained trials for the analysis were selected according to the correctness of the manual response, the fact that saccade latencies generate violation of the RMI suggests that the feature integration could not be attributed to a late, manual response production-related stage.

Although attentional and oculomotor systems present several common brain regions (Beauchamp et al., 2001; Corbetta et al., 1998), one proposed cortical locus for the oculomotor saliency map is the parietal eye field, located in the intraparietal sulcus. Although not directly expressed in term of saliency, Gaymard, Ploner, Rivaud, Vermersch and Pierrot-Deseilligny (1998) suggest on the base of studies investigating lesion effects of this cortical area that the motor program for top-down controlled saccades is developed in this particular cortical area.

However, more evidence speaks in favor of another candidate, the colliculus superior. The superficial layers of this midbrain structure receive direct input from retinal ganglion cells and the primary visual cortex which is organized in visuospatial maps (Lund, 1972). Receptive fields of collicular neurons are sensitive to motion contrasts (Davidson & Bender, 1991), making him a good candidate in orienting eye movements and exogenous attention. Cells of the colliculus superior are also activated in the execution of eye movements (Kustov & Robinson, 1996; Wurtz & Goldberg, 1972), as well in shifts of attention (Goldberg & Wurtz, 1972; Kustov & Robinson, 1996). A direct electrical stimulation of the neurons in the deep layers elicits saccades (e.g., Schiller & Stryker, 1972). Further, the receptive fields of these neurons are topologically arranged in an oculomotor map coding the size and direction of the electrically generated saccades (Robinson, 1972). Additionally, this structure was explicitly pointed out as a possible location of the visual saliency map (Corballis, 1998; McPeek & Keller, 2002; Reuter-Lorenz, Nozawa, Gazzaniga & Hughes, 1995). Its spatial organization of inputs and outputs as well as its activation during ocular and attentional shifts render thus the colliculus superior a suitable candidate for the neural correlate of the saccadic saliency map.

The similarity between manual and oculomotor RTs suggesting that signals are processed on the same mechanisms raises the issue of whether oculomotor and manual RTs are related. Stated differently, does the occurrence of saccades in trials affect latency of the manual RTs? In order to examine this question, all valid manual RTs were grouped into two categories, one category containing trials in which saccadic eye movements occurred while the search display was visible (corresponding to category 2) and the other category containing trials without saccades (pooling categories 1, 3 and 4). Observers with less than ten valid trials in each condition were excluded from the analysis; the data of eleven observers entered the analysis.

Results indicated that saccades incurred costs of 19.1 ms in manual reaction times ($t(10) = -5.20$, $p < .001$; trials with saccades: $M = 393.2$, $SD = 17.3$ ms, trials without saccades: $M = 374.2$, $SD = 15.5$ ms). A two-factors repeated-measures ANOVA with the factors eye movement (trials with saccades, trials without saccades) and target definition (color, orientation, redundant) showed significant main effects of the eye movement ($F(1,10) = 12.86$, $MS_e = 381.67$, $p < .05$) and target definition ($F(2,10) = 26.50$, $MS_e = 304.90$, $p < .001$). The interaction was not significant ($F(2,10) = .4$, $MS_e = 51.32$, $p > .10$). Multiple comparisons showed a significant difference of about 20 ms between the stages of the factor eye movement for each of the target definitions (color: $t(5) = -3.55$, $p < .05$; orientation: $t(5) = -3.82$, $p < .05$; redundant: $t(5) = -2.72$, $p < .05$; see Table 5.4), demonstrating that eliciting eye movements during the display onset slow down the manual RTs.

Table 5.4

Mean RTs (and standard deviations) for trials with and without saccades toward to target in the detection task of Experiment 1.

Target type	Without eye movements		With eye movements	
All	374.17	(15.47)	393.24	(17.32)
Color	349.63	(16.64)	370.14	(20.11)
Orientation	389.54	(23.11)	413.40	(23.76)
Redundant	340.94	(16.68)	366.62	(22.32)

Discussion

Results of detection task provided support that manual and saccadic RTs presented a similar processing architecture, namely a dimensionally-based saliency signal that would guide both attention and oculomotor system to the most salient object in the visual scene. Manual RT analysis demonstrated that, despite marginally significant redundancy gains, redundant targets were faster detected that color and orientation targets. Additionally, although not noticed in the entire set of observers, violations of the RMI were observed in a subgroup of observers, suggesting that visual features are processed according to a parallel co-active model, and consequently that both feature (saliency) signals are involved in the manual response triggering (Krummenacher et al., 2001, 200a, b).

A more marked support in favor of such a mechanism was provided by one of the oculomotor parameters. Saccadic RTs, or saccade latencies, were even more strongly affected by the target type than manual RTs; shorter saccade latencies were observed for redundant targets than for the color and orientation targets, leading to significant saccadic redundancy gains. Further, clear violations of the RMI were reported, suggesting that both features contribute to the elicitation of a saccade.

Altogether, these results suggest thus that the oculomotor system, if used, is controlled, as the attentional system (e.g., Wolfe, 1994) by a similar mechanism based on the spatial saliency. Further, comparing trials with and without eye movements revealed that eye movements lengthened manual RT suggesting that both systems interact.

5.3.2.2. Conjunction task

In the conjunction task, targets differing from distractors on both the color and orientation dimensions were presented only. For comparisons of the performance with single dimension trials, the RTs of the conjunction search condition are compared to RTs to the single-dimension targets of the detection task. Further, conjunction search data were compared to redundant-target trials of the detection task.

Behavioral data

Error rates. Error rates in the conjunction search task were low overall; observers missed on average 0.3 % of targets (*SD* = 0.8 %) and produced an average of 5.8 % of false alarms (*SD* = 4.9 %). The difference between proportions of misses and false alarms is statistically reliable ($t(12) = 4.16$, $p <. 01$) and is highly likely due to the nature of the task in which detection of the target is followed, on half of the trials with a go response whereas in the half of trials, observers are instructed to refrain from a response, even though one of the search items differs on two dimensions from the surrounding distractors. Inhibiting a response in the presence of a singleton object is more difficult than triggering a reaction.

Manual RTs. RTs to single dimension color and orientation targets in the detection task session were used as comparison standards for the targets defined both on the color and orientation dimensions in the conjunction task session. Due to the exclusion of one participant because of exceedingly high error rates in the conjunction search condition the mean color and orientation RTs of the detection search condition differ slightly from the values reported in the detection task section.

Manual RTs of the conjunction condition were analyzed in a one-way repeated-measures ANOVA with the factor target definition (color, orientation, color & orientation conjunction). The ANOVA revealed a significant main effect of target definition ($F(1.2,13.19) = 48.95$, $p < .001$, $MS_e = 4488.42$; Huynh-Feldt-corrected degrees of freedom). Conjunction targets ($M = 596.7$ ms, $SD = 74.9$ ms) were responded to significantly slower than color ($M = 402.9$ ms, $SD = 82.5$ ms, $t(11) = 15.64$, $p < .001$) and orientation targets ($M = 430.9$ ms, $SD = 70.3$ ms, $t(11) = 16.28$, $p < .001$).

This result is expected as observers, in the conjunction task, are required to process the identity of the target rather than the mere presence of an odd item in the search display.

Oculomotor parameters

Saccade and fixation parameters. The analyses of the eye movement parameters of the conjunctions search task involved the same steps as in the detection task. Data were first categorized according to the five categories a) trials without eye movements, b) rejected trials, c) eye movements while search display was visible, d) eye movements during and after search display was visible, e) eye movements after display had disappeared. Compared to the detection task, categorization results showed a completely different pattern than in detection task. By contrast to the detection task, only two out of 12 observers made eye movements in less than 50 % of the trials and the average proportion of trials with eye movements was 77.8 % ($SD = 22.8$ %) (see Table 5.5). This simple observation suggests that performing the conjunction search task requires that the target be fixated or, at the least, that the task is made easier if the target is fixated.

As in the detection task, trials were categorized according to whether a saccade was made to the target while the search display was visible or not. For the six observers who responded to the ten valid trials for condition, in trials without making a saccade to the target (39.3 % of trials), manual RTs were on average 61.6 ms faster ($t(5) = -3.77$, $p < .05$) than in trials in which a saccade was made (45 % of trials), 537.8 ms (no saccade) and 599.4 ms (saccade), respectively. That is, although moving the eyes substantially increased manual RTs, observers were not able to regularly adopt a strategy of forgoing saccades to the target to expedite manual RTs.

5.3.3. Comparison of performance in the detection and conjunction tasks

The main purpose of the present Experiment 1 was to investigate similarities and differences in manual (RT) and oculomotor parameters to targets defined by single color or orientation dimension differences by redundant (color and orientation) differences in the detection task and a conjunction of feature differences in the conjunction task. Redundant targets (of the detection task) and feature conjunction targets (of the conjunction task) were physically identical.

Table 5.5

Trial proportions as a function of the categories a) No Events, Events during the display onset b) rejected, c) accepted, d) Events during and after the display, and e) Events after the display onset, separately for each participant in the conjunction task condition of Experiment 1.

Observer	a)	b)	c)	Events	d)	e)
	No events	During display			During and after display	After display
		Rejected	*Accepted*	*Total*		
1	0.00	5.00	93.75	98.75	0.00	1.25
2	0.00	3.75	95.00	98.75	0.00	1.25
3	1.25	28.75	65.00	93.75	0.00	5.00
4	0.00	22.50	62.50	85.00	1.25	13.75
5	1.25	17.50	45.00	62.50	0.00	36.25
6	5.00	11.25	27.50	38.75	0.00	56.25
7	0.00	8.75	63.75	72.50	0.00	27.50
8	0.00	5.00	95.00	100.00	0.00	0.00
9	1.25	25.00	33.75	58.75	0.00	40.00
10	0.00	10.00	90.00	100.00	0.00	0.00
11	0.00	2.50	50.00	52.50	0.00	47.50
12	25.00	8.75	41.25	50.00	2.50	22.50
13	0.00	13.75	86.25	100.00	0.00	0.00
Mean	2.60	12.50	65.29	77.79	0.29	19.33

The results of Experiment 1 show significantly faster manual responses times for redundant targets in detection (396.0 ms) than to conjunction targets in conjunction (596.7 ms) task ($t(11) = -8.23$, $p < .001$), showing that, as expected, task requirements (detection of a saliency signal vs. establishing the identity of the target for multi-dimensional comparison with a template) modulate manual response times for physically identical objects (see Table 5.6 for mean RTs and standard deviations).

Of the oculomotor parameters, there were significant differences (note that only in seven observers there was a minimum of ten valid redundant target trials in the detection and conjunction targets in the conjunction search tasks).

Number of saccades ($t(8) = -.93$, $p > .05$), number of fixations ($t(8) = -.78$, $p > .05$) and fixation error ($t(5) = 1.55$, $p > .05$) did not differ between tasks. Latencies for the first saccade after display onset were shorter in the conjunction (176.4 ms) than in the detection (205.2 ms) task ($t(7) = 4.12$, $p < .01$).

In the conjunction task a substantially higher number of trials with saccades (*M* = 77.8 %, *SD* = 22.8 %) was observed than in the detection task (*M* = 55.8 %, *SD* = 28.6 %; $t(12) = -4.71$, $p < .001$).

Table 5.6

Mean values (and standard deviation) for manual and oculomotor parameters for redundant targets in detection and conjunction tasks (the values for targets defined in by a single dimension in detection task serve as comparison point between redundant targets of both paradigms).

Task	Detection				Conjunction	
Target type	Single		Redundant			
Reaction times (ms)	410.04	(76.26)	395.96	(20.47)	596.69	(21.63)
Fixation number	1.09	(0.13)	1.09	(0.11)	1.17	(0.32)
Saccade number	1.08	(0.12)	1.06	(0.08)	1.16	(0.32)
First saccade latency (ms)	223.49	(20.21)	205.17	(20.95)	176.43	(10.50)
First saccade landing error (px)	41.77	(13.36)	33.54	(9.03)	30.05	(6.18)
Inspection time percent (%)	67.64	(5.88)	64.92	(7.42)	45.59	(8.47)

5.3.4. Discussion

The results of Experiment 1 revealed two main findings about the organization of the oculomotor and visual attentional systems as well as the strategies applied by observers to perform visual search tasks that with different instructions. Although manual RTs in the detection task revealed a smaller mean RT redundancy gain (of about 5 ms) than observed in previous visual search studies (between 17 and 25 ms in Krummenacher et al.'s [2001, 2002a, b] singleton search tasks) and no overall violations of Miller's (1982) RMI were seen, a subset of observers, on the level of individual analysis, showed RMI violations in the first quantile, suggesting that color and orientation signals are processed in a parallel co-active fashion. Thus, overall, the present findings replicate earlier observations of parallel co-active processing in visual search for singleton feature targets by Krummenacher et al. (2001, 2002 a, b).

More importantly, there was a significant redundancy gain (of 9.7 ms) in the latencies of the first saccade after display onset as well as significant violations of the RMI. As stated in the discussion of the results of the detection task, expedited saccade latencies to redundant targets were interpreted as evidence that the saliency signal underlying oculomotor control in visual search (as proposed by Findlay and Gilchrist, 1998, see also Findlay & Gilchrist, 1998) operates on the same mechanism as the saliency signal assumed to control the allocation of focal attention in Wolfe's (1994) guided search model.

In a comparison of the detection and conjunction search tasks of Experiment 1, data show that task requirements modified the processing of physically identical (redundant and conjunction) targets. With respect to manual RTs, this result was of course expected as it has been shown in a number of studies (e.g., Treisman & Gelade, 1980), identification of the target item for comparison with a template requires access of the feature level and integration of multiple features across dimensions and both functions incur additional costs. More importantly, oculomotor parameters were also modulated.

Categorization of trials dependent on the presence of saccades to the target location while the search display was visible showed that the number of saccades depends on the task. In the detection task, the proportion of trials with saccades was comparably small, in the conjunction search task, the proportion was comparably large. Both proportions agree with previous reports of proportions of saccades made in feature search and conjunction search tasks[6] (Zelinsky & Sheinberg, 1997). The novel finding of this study is that observers, in both tasks, are not only able to perform the task without eye movements (this is expected for feature searches but not necessarily for conjunction searches) but that making a saccade towards the target location is associated with costs in manual RTs in both conditions.

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[6] Note that there were inter-individual differences in both tasks that will be worthwhile following up.

Processing of the identification of the target is possible with fixating it; the data even suggest that target identification is speeded if that target item is not fixated. Despite a substantial decrease in manual RTs, observers are not able to employ a strategy of forgoing saccades to the target in the conjunction search task, although they are well able to do so in the detection task. Further research is required to determine whether saccades to the target primarily contribute to an increase in sensitivity at the fixated location or whether they support inhibition of non-targets next to the target location. Using displays containing only the target item would contribute to differentiating between these possibilities.

The number of saccades and fixations that were executed while the search display was visible was not affected by the task. There were task differences, however: saccade latencies in the conjunction task were shorter than in the detection task. Shorter latencies in conjunction than in detection tasks were also found by Zelinsky and Sheinberg (1997), however, only for small set sizes of five items, with larger set sizes of 17 items, there was a tendency for latencies to be longer in the conjunction than in the detection task. In the present study, targets were always present in the conjunction task, (but not in the detection task), consequently, observers expectance probably decreased saccade latencies. Importantly, saccades also landed closer to the target in the conjunction than in detection task. This is an interesting finding as it suggests that higher accuracy is due to an endogenous factor. Note that (redundant and conjunction) targets are physically identical in both tasks, the conjunction task seems to require fairly that the target is fixated fairly accurately, and the (bottom-up) visual information available is modulated in such a way as to allow more accurate saccades to be planned in a shorter amount of time than in the detection task. Although pre-knowledge of target presence might be the main factor expediting saccade latencies, the latency difference suggests that saccades may server different purposes in the detection and conjunction tasks.

The reduced number of trials containing eye movements in detection task (as compared to the conjunction task) suggests that this task does not require eye movements to be solved adequately. It could be therefore envisaged that eye movements in detection task are elicited to confirm the presence of the target which was already detected by the attentional system. However, as reported above, such a confirmation affects manual RTs by lengthen the response time of about 20 ms.

Each of the tasks can be seen as one step towards identification. Imagine you are walking on the street and something suddenly enters your peripheral visual field. You do not have to move your eyes to detect this abrupt change, but, in order to consider whether it is potentially threatening, the objects identity needs to be established. While the present results suggest that it is not necessary to fixate the object for identification, having the eyes directed at the target certainly benefits perception of the further characteristics of the object such as its behavior or behavior changes. Here might be a reason for why to-be-identified targets are fixated even if the fixation comes at a cost.

According to Wolfe's (1994) Guided Search model, because the saliency signal is based on local feature contrasts, locations of salient objects are represented on the overall saliency map. Topographic saliency information is sufficient to complete a detection task; if a feature target is present, it generates a salient location on the map that triggers a response.

On the other hand, in the detection task, target foveating was not essential to detect the target presence. Similarly, some studies (Klein & Farell, 1989; Maioli et al., 2001) reported that precluding eye movements during a pop-out task did not degrade observers' performance, reinforcing the idea that identifying (i.e., foveating) the target in a pop-out detection task is no necessary task-relevant. Saccades in detection task could be therefore envisaged as a by-product generated by the visual system when target presence has to be reinsured. In such a case, saccades generation was subjected to the rules governing the overall oculomotor saliency map, in which a saccade is directed toward the strongest saliency signal on the map (stimulus-driven saccades). It could be therefore concluded that the oculomotor system adapts to task requirements.

5.4. Experiment 2

Task differences led to differences in oculomotor parameters in Experiment 1, even if the stimuli are physically identical. Most notably, saccade latencies were shorter and fixation errors were smaller in the conjunction compared to detection task. The exact reasons for these performance benefits could not be entirely explained on the basis of the results of Experiment 1, although it is likely that cognitive processes contribute to the effect. Experiment 2 was designed to address the issue of how the differences between tasks may be explained by modulating the visual input observers are presented with. In particular, Experiment 2 aimed to investigate the effects of spatially separating the dimensional signals that define redundant displays on oculomotor parameters. In Experiment 2, a visual search task introduced by

Krummenacher et al. (2002a) was used. Krummenacher et al. presented observers with single color or orientation targets and dual redundant color and orientation targets. In difference to the present Experiment 1, redundant target signals were presented at different, rather than the same spatial display location; put differently, instead of a differently colored and oriented target object, a differently colored plus a differently oriented target were shown. In addition, Krummenacher et al. manipulated the distance between the two target items in three steps: target items presented in adjacent locations, and with one or two distractors in between targets; as a control, single redundant targets (i.e. one search item defined on both dimensions) were presented. Krummenacher et al., investigating manual RTs, showed that single redundant targets are detected faster than dual redundant targets. Further, the larger the distance between the two dual redundant targets, the slower were RTs. Violations of Miller's (1982) RMI were observed in single as well as dual redundant targets, however, the probability of the RMI being violated decreased with increasing distance between dual redundant targets. Krummenacher et al. interpreted these results in terms of the spatial arrangement of the overall saliency signals. According Wolfe's (1994) Guided Search model, dimension-based saliency signals are integrated onto an overall saliency representation. Saliency activation signals the location of a conspicuous feature in the dimensional saliency modules. If the spatial locations of two signals coincide and they are integrated into the overall saliency representation in a parallel-co-active fashion, they are expected to generate a larger overall saliency peak and to exceed a threshold controlling the locations where attention is allocated at an earlier point in time. Under the same assumptions, if dimensional signals are more and more distant, the smaller the space in which they overlap becomes and, consequently, the longer it takes for the threshold to be exceeded.

In the present Experiment 2, a comparable experimental setup was used in a detection task. In detail, in two consecutive sessions, observers had to indicate the presence of single redundant targets in the first session and dual redundant targets separated by one, two or three units of distance in the second session.

The results of Experiment 1 showed that fixations of the target, in the detection task, are not necessary to indicate target presence. Therefore, it is safe to assume that target fixations are not required in Experiment 2, either. More importantly, if the saliency representation that governs saccade programming functions on the same mechanisms as the saliency representation that controls attention allocation the latencies of the first saccades after display onset to dual redundant targets should vary as a function of the distance between targets. As the two dimensional signal (i.e., the features defining the target) occupy the same spatial location, under the assumption of the same function mechanisms for attention and oculomotor saliency, single redundant targets should generate a single and larger peak of saliency on the overall saliency map, whereas dual targets generate independent and smaller activations; the difference in saliency is expected to be reflected in latencies differences for saccades to single vs. dual redundant targets. Moreover, saccade latencies are expected to be affected by the distance between dual redundant targets, larger distances should reduce the magnitude of redundancy gains. In other words, latencies of saccades to dual redundant targets, independently of their spatial distance, cannot be faster than the fastest latencies to single redundant targets.

One important aspect in investigations into the ocular target selection under dual redundant target conditions is the examination of potential effects of the arrangement of dual targets on the landing site of saccades. The first saccade after display onset might be directed at either one of the dual targets or the saccade might land between the two targets. Findlay (1982, Exp. 1) reported that when a participant was instructed to track a point jumping rapidly away from or back to the central fixation point saccades tended to land between the central fixation point and the peripheral fixation target (peripheral fixation points were located at equal distances to the left or right of fixation). In a visual search experiment with trials containing two identical targets, in which search objects were arranged on a virtual circle, Findlay (1997) showed that, when observers had to saccade as quickly as possible to the target(s), saccades landed between the two targets when they were adjacent. This phenomenon is commonly referred to as the “global effect” and observed when the distance separating dual targets is smaller than the size of the visual receptive field of the cell assembly representing the peripheral targets. Stated differently, the two targets are represented as a single activation peak in the receptive that underlies saccade programming. The magnitude of the global effect can be influenced by the nature of the task. Findlay (1982) in Experiments 2 and 3 presented one or two squares to the left or the right of the fixation point and observers had to indicate whether a gap was present in one object or not. In dual object trials, when the objects were identical, the first saccade landed closer to (and slightly beyond) the near target, that is, saccade distance was highly accurate. In contrast, when one of the squares was larger than the other one, the first saccade landed near the larger of the two squares. Findlay argued that, because the “mass” of the global configuration was unbalanced when one target was larger than the other, the center of gravity of the whole configuration was displaced toward the larger target. Translated into the terms of a saccadic saliency map, these results can be interpreted as an integration of saliency signals of the larger and smaller target object; the weight of the larger object is higher but the smaller object shifts the peak of saliency away from the larger object. Stated differently, in the case of an "unbalanced" display (i.e., a display with differently sized objects), saccades might still tend to be controlled by the overall configuration (the global effect), but the larger target generates the stronger saliency signal, biasing saccade direction in its favor.

Applied to the dual redundant target trials of Experiment 2, the effect of spatial arrangement leads to the assumption that the selection of the location of the first fixation depends on the relative saliency of the two target-defining dimensions (color and orientation). As color targets are usually responded to somewhat faster than orientation targets, saccade generation is expected to be controlled mainly by the color signal, that is, saccades are expected to be directed to or nearer the color-defined target.

5.4.1. Method

Observers. Thirteen observers (nine female and four male) took part in Experiment 2. All were students at the University of Fribourg. They received course credits or were paid CHF 25 for participation. Observers' age ranged between 21 and 29 year (median = 25 years). All of the observers had a normal or a corrected to normal vision, including color vision.

Apparatus and setting. Observers were seated in a darkened room in front of a high-resolution CRT 17" monitor run with a spatial resolution of 1024 x 786 pixels and a refresh rate of 60 Hz and driven by a Hewlett Packard PC running Windows XP. The distance between participant and monitor was approximately 57 cm. The experiment was controlled by a MatLab script using the PsychoPhysics and EyeLink Toolbox extensions (Brainard, 1997; Pelli, 1997; Cornelissen, Peters & Palmer, 2002; see http://psychtoolbox.org/). Eye movements were recorded at a rate of 250 Hz by an EyeLink I system (SR Research Ltd., Version 2.11). Eye to monitor distance was held constant with an adjustable chinrest and two references indicating correct forehead position. The system was calibrated using the nine-point calibration procedure provided by the manufacturer at the beginning of the experiment. In order to ensure the accuracy of measurement, a drift correction was executed at the beginning and middle of each block.

Stimuli. Search stimuli were 36 green vertical bars subtending .88° x .2° of visual angle presented on a grey background (RGB: 87, 87, 87). The colors roughly isoluminant (RGB code for green: 0, 200, 0). The bars stimuli were arranged in a virtual matrix 6 x 6 rows and columns subtending 13.51° x 13.51° of visual angle. The positions of search items was randomly jittered relative to the center of the cell, in each trial (±0.5° along the horizontal and vertical axes) to prevent collinearity of search items. The minimum (maximum) distance between centers of gravity of neighboring items was 1.71° (3.71°) horizontally and vertically.

There were three target conditions, a) single targets defined in a dimension (color: red [255, 0, 0], blue [0, 0, 255]; or orientation (bar tilted 45° to the left or right); b) single redundant targets defined in two dimension (color and orientation), and c) dual redundant targets (one target defined in the color, the other one in the orientation dimension). The distance between dual redundant targets was varied in three steps: dual targets were either presented at neighboring display locations (horizontal, vertical or diagonal shifts were possible), or separated by one or two distractor locations; distances are referred to as distances 1, 2 or 3 respectively (see Figure 5.3 for examples).

Procedure and design. Experiment 2 was split in five sessions that were run on two different days. Each session took about 25 minutes to complete. Depending on the participant's fatigue, either two or three sessions were run on the first day. In each session, displays without targets and with singly defined targets were presented. The type of redundantly defined targets was controlled with single redundant targets shown in the first session only and dual redundant targets shown in the following four sessions. In the first session with single redundantly defined targets, observers had to complete one short exercise block of 16 trials (4 non-target, 4 color target, 4 orientation target and 4 single redundant target trials) and five experimental blocks of 58 trials each. Each block contained 22 non-target trials (38% of trials), and 12 trials of each of the target-present conditions. In sessions two to five, an initial "warm-up" block of 30 trials (10 target-absent, 4 color, 4 orientation and 12 dual redundant targets, one for each condition at each distance) and 5 experimental blocks of 48 trials were completed. Each experimental block contained 24 non-target trials (50% of trials), 6 color targets, 6 orientation targets and 12 dual redundant targets, one for each feature combination at each distance.

In all sessions, observers were instructed to press the left-hand "Ctrl"-key when the all the bars were green and vertical (target-absent) and the right-hand "Ctrl"-key of a standard computer keyboard, when one or two items (according to condition) differed from all the other items (target-present). The instructions are presented on the compute screen at the beginning of the warm-up blocks. Further, observers were instructed orally by the investigator. They were told that they could just ignore the eye tracker.

Data analysis. Data analysis in Experiment 2 follows the steps of Experiment 1.

5.4.2. Results

Results are presented in three sections. Sections one and two separately analyze the single redundant target session and the dual redundant target sessions, respectively. Each section contains three subsections for manual RTs, oculomotor parameters and the comparison of manual RTs for trials with and without eye movements while the search display was visible. The final section three compares performance for the two types of redundant (single vs. dual) targets.

5.4.2.1. Single redundant targets

Behavioral data

Errors. Error rates were low overall, none of the observers produced error rates above 10% of trials. On average, the rate of extreme RTs (i.e., RTs smaller than 100 ms or larger than 1600 ms) was 1.4 % (*SD* = 1 %). Trials with extreme RTs were excluded from analysis. Incorrect responses were observed in 2.7 % of the trials (*SD* = 2.1 %). The difference between false alarms (*M* = 3.9 %, *SD* = 4.4 %) and misses (*M* = 2.0 %, *SD* = .6 %) was not significant ($t(12) = 1.59$, $p > .05$). However, miss rates in single redundant target trials (0.6 %) were significantly smaller than in color (1.2 %) and orientation (4 %) target trials ($F(1.52,18.22) = 7.63$, $MS_e = 6.83$, $p < .01$; Huynh-Feldt-corrected degrees of freedom). The result of lower miss rates to redundant targets replicates earlier findings by Krummenacher et al. (2002a).

Manual RTs. Manual RTs were subjected to a one-way repeated-measures ANOVA with the factor target definition. The ANOVA showed a significant main effect of target dimension ($F(1.30,15.57) = 29.95$, $MS_e = 332.75$, $p < .001$; Huynh-Feldt-corrected degrees of freedom). Single redundant targets (*M* = 378.6 ms, *SD* = 57.3 ms) were detected significantly faster than color targets (*M* = 387.9 ms, *SD* = 52.3 ms, $t(12) = 4.88$, $p < .05$); color targets were also detected faster than orientation targets (*M* = 421.0 ms, *SD* = 70.2 ms, $t(12) = 5.66$, $p < .05$; see Table 5.7 for means RTs.) Further, testing for RT redundancy gains according to the procedure proposed by Miller and Lopes (1988) revealed a significant advantage of 10.1 ms (*SD* = 2.89, $t(12) = 3.5$, $p < .01$) for single redundant targets relative to the faster of RTs to targets defined on one dimension (color or orientation).

Table 5.7

Mean RTs and miss rates, separately for color, orientation and single redundant trials of session 1 (single redundant targets).

			Error Rates (%)			
Target type	RT (ms)		Misses		Extremes	
Color	387.94	(52.35)	1.41	(1.78)	1.54	(1.98)
Orientation	421.01	(70.18)	3.97	(3.97)	1.54	(3.51)
Redundant	378.55	(57.32)	0.64	(1.08)	1.79	(1.08)

Analysis of the entire RT distribution did not reveal statistically significant violations of the Miller's (1982) Race Model Inequality (Figure 5.4, panel a). However, eight (out of 13) observers showed smaller summed probabilities of having responded, at time t, to a target defined on one dimension only than the comparison standard probability for redundant targets in at least one quantile (with numerical violations in 5 quantiles on average, and a range form 1 to 10 quantiles for different observers).

Taken together, the analyses of manual RTs can be taken to suggest that color and orientation signals, in the single redundant target condition of Experiment 1, were processed in a parallel co-active fashion.

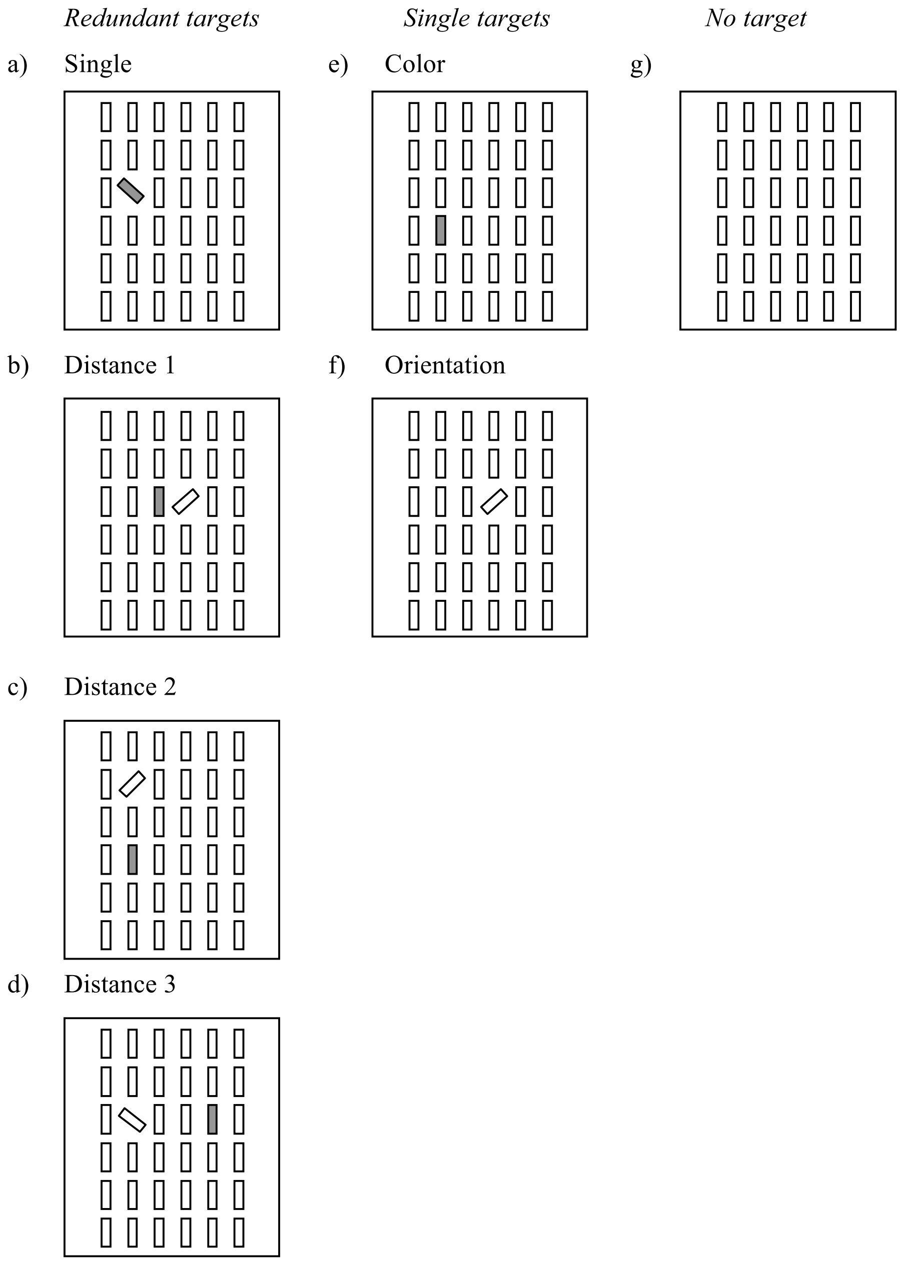

Figure 5.3. Illustration of displays presented in Experiment 2. Panels a) to d) illustrate redundant target conditions. The target in panel a) is a single redundant bar defined on both the color and orientation dimensions, panels b) to d) show dual redundant targets separated, respectively, by one, two and three distance units. Panels e) and f) show single target conditions, and panel g) present a target-absent display.

Oculomotor parameters

The criteria for oculomotor parameters established in Experiment 1 were applied to the data of Experiment 2. Following the criteria, the data sets of four (of the 13) observers were not included in the analyses of oculomotor parameters. The categorization of trials into the categories a) trials without eye movements, b) rejected trials, c) eye movements while search display was visible, d) eye movements during and after search display was visible, e) eye movements after display had disappeared (see Table 5.8) showed that in 52.6 % of trials eye movements were made while the search display was visible; of these 43.2 % were directed toward the target; half of the observers (seven/13) made eye movements in at least 50% of the trials. Note that, as in Experiment 1, there was a high inter-individual variability in the occurrence of eye movements, the probability of executing saccades ranged from a minimum 17.9 % of trials to 99.0 % of trials.

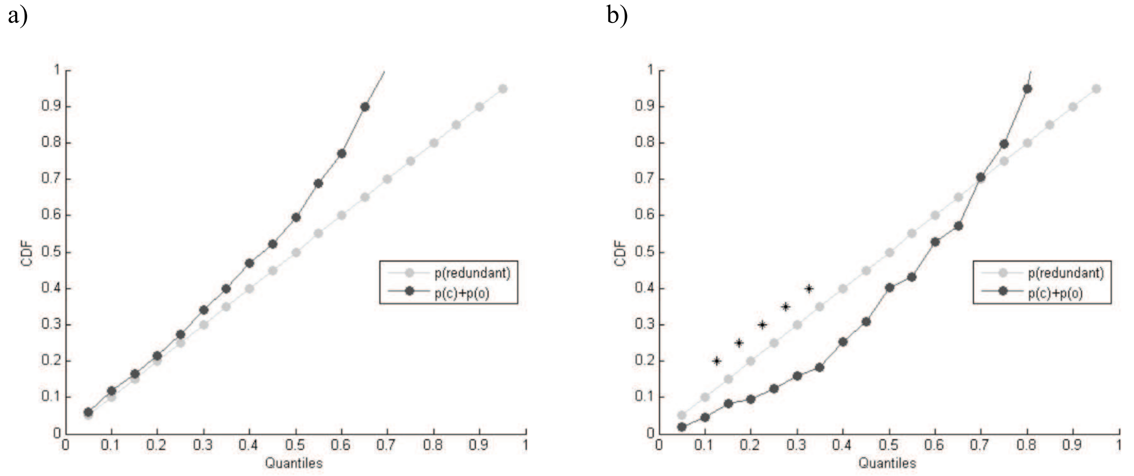

Figure 5.4. Results of the tests for violations of Miller’s (1982) RMI a) in manual RTs and b) in saccadic latencies in the single redundant detection task of Experiment 2. The dark grey curve represents the cumulative probability function for the summed probabilities of RTs to single targets having occurred at a given time t; the light grey curve represents corresponding redundant target probabilities. Significant violations are marked with a star ($p < .05$). Note that for the RMI to be satisfied, summed single dimension probabilities must be no smaller than redundant target probabilities.

Table 5.9 presents means and standard deviations for number of fixations and numbers of saccades (per trial while the search display was visible), latency of the first saccade after display onset, fixation error (in pixel), and proportional inspection time, separately for each of the three target definitions.

Table 5.8

Trial proportions as a function of the categories a) No Events, Events during the display onset b) rejected, c) accepted, d) Events during and after the display, and e) Events after the display onset, separately for each participant in the single redundant target condition of Experiment 2.

Observer	a)	b)	c)	Events	d)	e)
	No events	During display			During and after display	After display
		Rejected	*Accepted*	*Total*		
1	0.94	5.52	57.93	63.45	1.38	32.07
2	0.42	0.69	24.48	25.17	1.38	72.07
3	0.10	16.90	46.55	63.45	1.03	35.17
4	1.46	14.48	36.90	51.38	3.10	40.69
5	5.83	5.86	12.07	17.93	1.38	61.38
6	0.00	5.17	93.79	98.97	0.00	1.03
7	0.42	8.28	6.21	14.48	1.03	83.10
8	1.25	2.41	24.83	27.24	0.00	68.62
9	0.00	26.21	68.97	95.17	0.69	4.14
10	2.71	5.17	21.38	26.55	0.00	64.48
11	0.94	6.21	38.28	44.48	5.17	47.24
12	0.10	13.45	47.24	60.69	0.69	38.28
13	0.31	11.38	83.10	94.48	0.69	3.79
Mean	1.11	9.36	43.21	52.57	1.27	42.47

Separate repeated-measures ANOVAs of the oculomotor parameters with the factor target definition (color, orientation, single redundant) showed significant differences for the latencies of the first saccade after display onset (*F*(2,18) =48.79, MS_e = 50.01, *p* < .001) and landing error (*F*(2.18) =5.62, MS_e = 9.75, *p* < .05). Simple contrasts to follow-up the main effects showed that first saccade latencies to single redundant targets (*M* = 202.3 ms, *SD* = 22.8 ms) were significantly shorter (*t*(8) = 5.23, *p* < .01) than latencies to color targets (*M* = 213.9 ms, *SD* = 25.4 ms); color target latencies were shorter (*t*(8) = 5.52, *p* < .01) than latencies to orientation targets (*M* = 233.4 ms, *SD* = 28.4 ms). Follow-up test for landing error showed that saccades to redundant targets (deviation of *M* = 34.1 pixels, *SD* = 6.3 pixels) landed significantly closer (*t*(8) = 2.68, *p* < .05) to the target than saccades to orientation targets (*M* = 38.8 pixels, *SD* = 6.8 pixels); landing error for single redundant and color targets did not differ significantly (*t*(8) = 1.52, *p* > .10). Testing for mean RT redundancy gains in saccade latencies following the procedure by Miller and Lopes (1988) revealed a significant redundancy gain for latencies of first saccades (*t*(9) = 4.04, *p* < .01) of 13.5 ms (*SD* = 10.5 ms). Analysis of the entire RT distribution for violations of Miller's (1982) RMI revealed significant violations for quantiles 3 to 7 (see Figure 5.4, panel b). (According to the criterion requiring a minimum of thirty valid trials for each target type, only four observers were included in the test for violations of the RMI.)

Note that no significant difference between target definitions were observed for number of fixations ($F(2,18) = 1.55$, $MS_e = .002$, $p > .05$) and saccades ($F(1.10,9.80) = 3.72$, $MS_e = .002$, $p > .05$) [and inspection time percent ($F(2,18) = 1.74$, $MS_e = 3.48$, $p > .05$)].

In the final section, manual RTs of trials with and without saccades to the target were compared. Observers with less than ten valid trials per condition were excluded from analysis. Although the average difference in manual RTs for trials with and without eye movements (*M* = 424.8 ms, *SD* = 71.3 ms vs. *M* = 413.4 ms, *SD* = 64.3 ms, respectively) was statistically not significant ($t(11) = -1.65$, $p > .10$), executing a saccade incurs an average cost of 31.2 ms in target-absent trials (*M* = 476.9 ms, *SD* = 88.8 ms vs. 445.7 ms, *SD* = 68.4 ms; $t(9) = -3.77$, $p < .01$) and 10.1 ms in target-present trials (*M* = 382.2 ms, *SD* = 44.2 vs. 372.0 ms, *SD* = 46.9 ms; $t(9) = -2.09$, $.05 < p < .10$).

Table 5.9

Mean values (and standard deviation) for the five oculomotor parameters in each target type for the single redundant targets session.

Target type	Fixation number	Saccade number	Saccade latency (ms)	Landing error (px)	Inspection time (%)
Color	1.03 (.05)	1.02 (.04)	213.90 (25.38)	36.88 (4.65)	64.11 (6.45)
Orientation	1.06 (.09)	1.06 (.09)	233.25 (28.26)	38.77 (6.81)	64.20 (6.38)
Redundant	1.04 (.05)	1.02 (0.03)	202.33 (22.78)	34.11 (6.31)	62.81 (7.44)

A two-way repeated-measures ANOVA of manual RTs (see Table 5.10) with the factor eye movement (with movements, without movements) and target definition (color, orientation, single redundant) showed that trials with eye movements do not present faster RTs than trials without eye movements ($F(1,6) = 3.29$, $MS_e = 111.96$, $p > .10$; Huynh-Feldt-corrected degrees of freedom). The interaction between both factors was not significant as well ($F(2,12) = .001$, $MS_e = 73.87$, $p < .10$).

Table 5.10

Mean RTs for trials with and without eye movements in single redundant targets session.

Target type	Without eye movements	With eye movements
Color	365.13 (43.99)	371.10 (47.36)
Orientation	398.35 (68.20)	404.14 (61.85)
Redundant	352.93 (51.49)	358.94 (50.34)

5.4.2.2. Dual redundant targets

Behavioral data

Errors. Two observers were excluded from all the following analyses because of error rates in excess of 10%. On average, 1.4 % (*SD* = .4 %) of all RTs of the remaining eleven observers were considered extremes and excluded from analysis. Error rates were low overall, 2.7 % (*SD* = 2.1 %) were responded to erroneously. No significant difference was observed between false alarm (3.1 %, *SD* = 2.6 %) and miss rates (3.2 %, *SD* = 2.2 %; $t(10) = -.28$, $p > .05$). A repeated measures ANOVA revealed that miss rates differed according to the target type ($F(1.07,10.72) = 15.51$, $\mathrm{MS_e} = 15.01$, $p < .01$; Huynh-Feldt-corrected degrees of freedom). Multiple comparisons showed that miss rates in orientation target trials (*M* = 8.2 %, *SD* = 5.8%) were significantly higher than in color (*M* = 2.3 %, *SD* = 1.7 %; $t(10) = 3.66$, $p < .01$) and dual redundant target trials (*M* = 2.4 %, *SD* = 2.1 %; $t(10) = 4.60$, $p < .01$).

Manual RTs. Table 5.11 presents mean RTs as a function of the target definition (color, orientation, redundant) and, for dual redundant targets, of spatial separation between targets. Mean RTs were analyzes in a one-way repeated-measures ANOVA with the factor target definition (color, orientation, dual redundant). The ANOVA revealed the main effect to significant ($F(2,20) = 23.22$, $\mathrm{MS_e} = 182.88$, $p < .001$). Dual redundant targets (M = 405.4 ms, *SD* = 63.2 ms) and color targets (*M* = 409.2 ms, *SD* = 60.88 ms) were detected significantly faster than orientation targets (*M* = 441.2 ms, *SD* = 63.16; respectively, $t(10) = 5.54$, $p < .01$ and $t(10) = 4.70$, $p < .01$), while dual redundant and color target RTs were not statistically different ($t(10) = 1.12$, $p > .10$). In contrast to Krummenacher et al.'s (2002a) result, search RT was not affected by the distance between dual redundant targets ($F(2,20) = .12$, $\mathrm{MS_e} = 84.93$, $p > .05$), nor the miss error rate ($F(2,20) < 1$, $p < .10$.). As expected on the basis of the lack of a difference between dual redundant and color targets, the test for redundancy gains according to the procedure of Miller and Lopes (1988) did not revealed significant RT redundancy gains for the pooled dual redundant target RTs (average gain: 3.5 ms, $t(10) = 1$, $p < .10$). Separate tests for redundancy gains were conducted for dual redundant targets separated by 1, 2 or 3 units of distance; results show that redundancy gains in neither of the distance conditions were statistically reliable (distance 1: mean gain = 4.4 ms, $t(10) = 1.29$, $p > .05$); distance two: mean gain = 2.5 ms, $t(10) < 1$, $p < .10$); distance 3: mean gain = 3.7 ms, $t(10) < 1$, $p < .10$.).

Table 5.11

Mean RTs and error rates for each trial type in the dual redundant targets sessions.

Trial type	RT (ms)		Error rates (%)			
			Misses		Extremes	
No target	403.147	(60.50)	3.09	(2.35)	1.84	(0.39)
Color	409.22	(60.88)	2.27	(1.71)	1.29	(0.94)
Orientation	441.17	(73.93)	8.18	(5.81)	1.52	(0.73)
Redundant						
All	405.38	(63.16)	2.42	(2.12)	1.06	(0.84)
Distance 1	404.51	(62.26)	1.14	(1.53)	0.91	(0.98)
Distance 2	406.38	(64.08)	1.14	(1.18)	0.34	(0.58)
Distance 3	405.19	(64.51)	1.36	(1.42)	0.34	(0.81)

Similarly, analyses of the entire reaction time distributions did not reveal any significant violation of Miller’s (1982) RMI in any of the three distance conditions (see Figure 5.5). However, a closer look at the violations of the RMI on the level of individual distributions suggested that the number of numerical violations of the RMI (smaller summed probabilities for responses to non-redundantly defined targets having occurred at time t than the comparison probabilities to redundant targets) decreases as a function of the distance between dual targets. In the analysis of RTs pooled over all distances, an average of 1.7 violations was observed in three observers. Analysis of dual redundant targets separated by distance 1, 3.3 violations were observed in seven observers, whereas 2 violations in two observers in targets separated by distance 2, and 2 violations in nine observers in targets separated by distance 3 were found.

Eye movement parameters. Categorization of trials into the categories a) trials without eye movements, b) rejected trials, c) eye movements while search display was visible, d) eye movements during and after search display was visible, e) eye movements after display had disappeared (given in Table 5.12) showed that in 44.8 % of the trials eye movements were made while the search display was visible, 38.9 % (i.e., less than half) of these saccade were directed toward the target. Four (of 13) observers made an eye movement in at least 50 % of the trials. (As in the single redundant target condition, the occurrence of eye movements show large is characterized by large inter-individual variability with eye movements made in a range between 18.1 % to 95.5 % of trials).

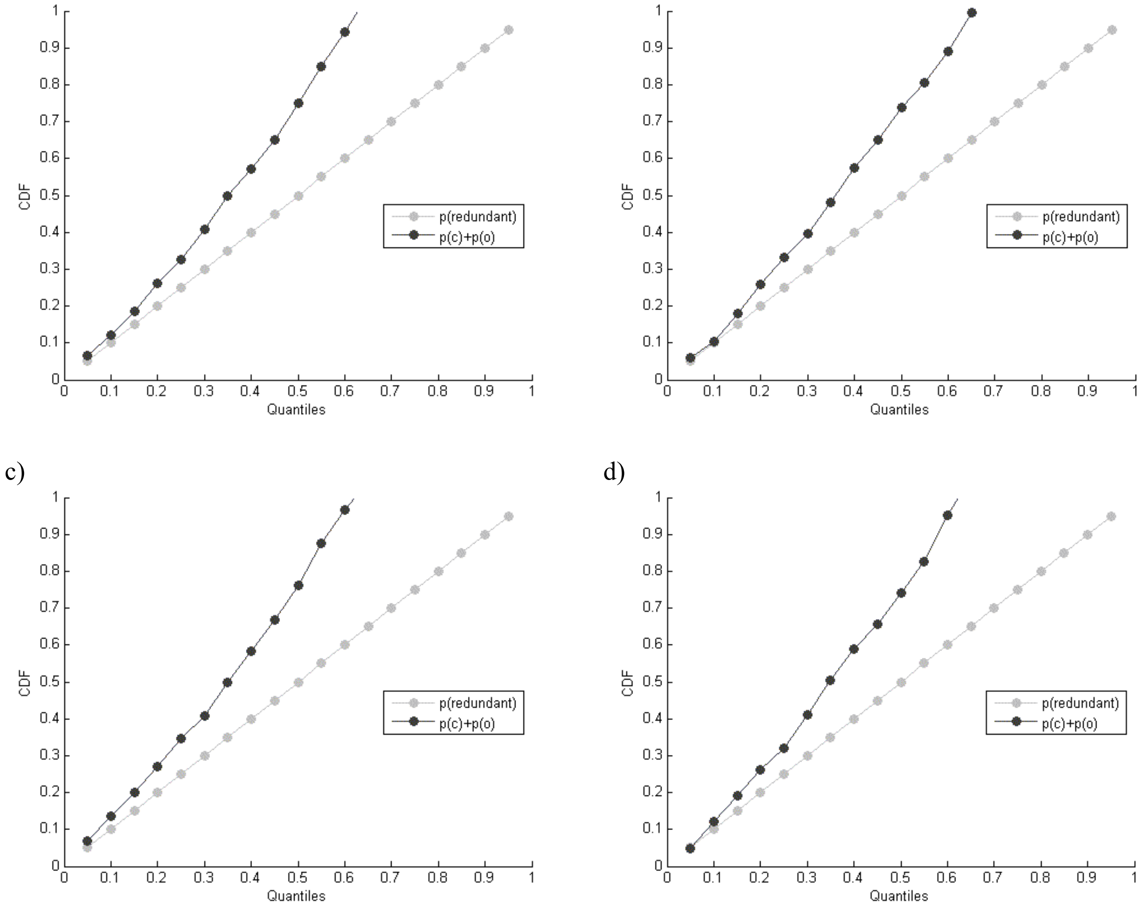

Figure 5.5. Results of the tests for violations of Miller’s (1982) RMI in manual RTs in the detection task of Experiment 1 including; Violation of the RMI a) for all dual redundant targets, b) for dual redundant separated by one unit, c) for dual redundant separated by two units, d) for dual redundant separated by three units. The dark grey curve represents the cumulative probability function for the summed probabilities of RTs to single targets having occurred at a given time t; the light grey curve represents corresponding redundant target probabilities. Note that for the RMI to be satisfied, summed single dimension probabilities must be no smaller than redundant target probabilities.

Due to the small percentage of trials with eye movements that entered the analyses according to the criterion defined in the Methods section of Experiment 1, eye movement data of seven observers entered the analyses of oculomotor parameters (recall that observers with fewer than a minimum of 10 trials for each of the three distances of dual redundant targets were excluded from analysis).

Table 5.13 presents parameters for fixation and saccade number, saccade latency, landing error and inspection time, separately for color, orientation and dual redundant target trails. Oculomotor parameters were analyzed in separate one-way repeated-measures ANOVAs with the factor target definition (color, orientation, dual redundant). The ANOVAs did not reveal significant main effects for numbers of fixations ($F(2,12) = 2.77$, $\mathrm{MS_e} = .002$, $p > .10$) and saccades ($F(2,12) = 1.53$, $\mathrm{MS_e} = .002$, $p > .10$). A repeated-measures ANOVA with the factor distance (distances 1, 2, 3) showed that distance between dual targets neither affected number of fixations ($F(2,12) = .14$, $\mathrm{MS_e} = .001$, $p > .10$) nor number of saccades ($F(2,12) = .25$, $\mathrm{MS_e} = .002$, $p > .10$) made in dual redundant target trials.

Table 5.12

Trial proportions as a function of the categories a) No Events, Events during the display onset b) rejected, c) accepted, d) Events during and after the display, and e) Events after the display onset, separately for each participant in the dual redundant target condition of Experiment 2.

Observer	a)	b)	c)	Events	d)	e)
	No events	During display			During and after display	After display
		Rejected	*Accepted*	*Total*		
1	2.19	7.19	55.31	62.50	1.88	33.44
2	0.10	0.94	17.19	18.13	1.04	80.73
3	0.94	4.38	33.44	37.81	0.73	60.52
4	2.08	14.38	23.85	38.23	2.81	56.88
5	25.83	3.23	19.48	22.71	2.71	48.75
6	0.10	5.42	87.29	92.71	0.00	7.19
7	1.15	5.73	13.23	18.96	0.83	79.06
8	0.94	4.79	23.02	27.81	0.31	70.94
9	0.42	10.83	84.69	95.52	0.63	3.44
10	6.15	5.00	15.94	20.94	1.04	71.88
11	9.06	4.17	25.21	29.38	3.02	58.54
12	2.81	5.52	83.75	89.27	0.83	7.08
13	5.83	5.00	23.02	28.02	1.04	65.10
Mean	4.43	5.89	38.88	44.77	1.30	49.50

However, landing error ($F(2,12) = 11.16$, $\mathrm{MS_e} = 77.49$, $p < .01$) was affected by target dimension. The first fixation after display onset was significantly closer to the target when targets were redundantly defined (M = 30.0 pixels, SD = 4.2 pixels) than when targets were singly defined (color = 36.1 pixels, SD = 6.7 pixels, $t(6) = 2.59$, $p < .05$; orientation = 39.0 pixels, SD = 4.2 pixels, $t(6) = 3.18$, $p < .05$). Further, in trials with dual redundant targets separated by three units of distance (M = 40.6 pixels, SD = 6.8 pixels) saccades landed at a location more distant to one of the dual targets than saccades to dual redundant targets separated by one (M = 22.8 pixels, SD = 3.4 pixels) and two units (M = 28.5 pixels, SD = 6.3 pixels; $F(2,12) = 21.44$, $p < .001$, $\text{MS}_e = 21.15$; linear trend: $F(1,6) = 57.56$, $p < .001$, MS_e = 19.37).

Table 5.13

Mean values (and standard deviation) for the five oculomotor parameters in each target type for the dual redundant targets session.

Condition	RT (ms)	Fixation number	Saccade number	Saccade latency (ms)	Landing error (px)	Inspection time (%)
Single redundant targets						
Color	396.65 (52.35)	1.03 (.04)	1.02 (.04)	215.75 (27.43)	36.84 (5.03)	63.06 (5.94)
Orientation	431.72 (71.23)	1.07 (.10)	1.06 (.09)	232.28 (32.43)	39.31 (8.03)	62.43 (4.97)
Redundant	390.44 (53.99)	1.05 (.11)	1.02 (.09)	204.88 (26.48)	34.79 (7.31)	61.37 (6.77)
Dual redundant targets						
Color	409.21 (60.88)	1.04 (.05)	1.03 (.05)	219.25 (24.12)	36.12 (6.65)	62.52 (6.53)
Orientation	441.17 (73.96)	1.07 (.09)	1.06 (.09)	243.65 (41.99)	38.95 (7.44)	64.05 (5.76)
Redundant						
All	405.38 (63.13)	1.10 (.11)	1.07 (.09)	231.61 (27.05)	29.99 (4.22)	67.06 (5.54)
Distance 1	404.51 (62.26)	1.11 (.12)	1.07 (.08)	228.40 (29.40)	22.79 (3.43)	66.61 (5.81)
Distance 2	406.38 (64.08)	1.10 (.13)	1.08 (.12)	237.58 (27.28)	28.45 (6.26)	68.81 (5.37)
Distance 3	405.19 (64.51)	1.10 (.10)	1.08 (.09)	231.51 (28.51)	40.63 (6.83)	66.04 (5.00)

[Percent of inspection time was also affected by target dimension ($F(2,12) = 7.44$, MS_e = 5.02, $p < .05$); Multiple comparisons showed that dual redundant target (M = 67.1 %, SD = 5.5 %) presented a longer inspection time than color (M = 62.5 %, SD = 6.5 %, $t(6) = 4.09$, $p < .05$) and orientation targets (M = 64.1 %, SD = 5.8 %, $t(6) = 3.54$, $p < .05$), whereas color and orientation targets did not differ significantly ($t(6) = -1.00$, $p > .10$). When dual redundant targets were split into distances ($F(2,12) = 6.60$, $\text{MS}_e = 2.27$, $p < .05$; quadratic trend: $F(1,6)$ = 28.86, $\text{MS}_e = 2.53$, $p < .01$), there was a tendency for inspection time to be longer when dual redundant targets were spatially separated by distance 2 (M = 68 %, SD = 5.4 7%) than by distance 1 (M = 66.6 %, SD = 5.8 %, $t(6) = -3.22$, $.05 < p < .10$) or distance 3 (M = 66 %, SD = 5.1 %, , $t(6) = 3.18$, $.05 < p < .10$), but there was not significant difference between distance 1 and 3 ($t(6) = .68$, $p > .10$)]

Finally, target dimensions significantly affected latencies of the first saccade after display onset ($F(2,12) = 7.55$, $MS_e = 146.95$, $p < .01$). Latencies to color targets ($M = 219.2$ ms, $SD = 24.1$ ms) were significantly shorter than to dual redundant ($M = 231.6$ ms, $SD = 17.1$ ms; $t(6) = -3.92$, $p < .05$) and orientation targets ($M = 243.7$ ms, $SD = 17.1$ ms, $t(6) = -3.32$, $p < .05$). Analysis of the different distances separating dual redundant targets revealed a significant main effect of the distance ($F(2,12) = 6.58$, $MS_e = 23.59$, $p < .05$; quadratic trend: $F(1,6) = 7.63$, $MS_e = 37.24$, $p < .05$). Multiple comparisons showed only that marginally longer saccade latencies ($t(6) = -3.11$, $.05 < p <.10$) for dual targets separated by two ($M = 237.6$ ms, $SD = 27.3$ ms) than by one unit of distance ($M = 228.4$ ms, $SD = 29.4$ ms); dual targets separated by three distances did not differ significantly from dual targets separated by one ($t(6) = -1.63$, $p > .10$) or two units ($t(6) = 2.18$, $p > .10$).

Because saccade latencies were found to be fastest to single color targets, redundant targets caused latency costs rather than benefits. As in the case of mean RT redundancy gains, the analysis procedure proposed by Miller and Lopes (1988) can by applied to test whether the "redundancy costs" in dual redundant target trials compared to single target trials are statistically reliable. Redundancy costs were examined for dual redundant targets separated by 1, 2 or 3 units of distance. The tests showed costs 9.4 ms ($t(6) = -3.09$, $p < .05$), 18.6 ms ($t(6) = -5.40$, $p < .01$), and 12.2 ms ($t(6) = -3.97$, $p < .01$) (average costs across distances: 12.6 ms; $t(6) = 4.75$, $p < .01$).

Analogous to manual RTs, analyses of the entire distribution of latencies of the first saccade after display onset did not reveal any significant violations of Miller's (1982) RMI (see Figure 5.6). Interestingly, a closer look at an individual data sets revealed a trends of violations of the RMI similar to the one reported by Krummenacher et al.'s (2002a). Although only three observers showed violations of the RMI for two, four and three quantiles, respectively, the number of quantiles with violations decreased with distance between the two dual targets. With a spatial separation of one unit, five observers (out of nine showed on average 3.2 quantiles with violations of the RMI, whereas an average of 2 quantiles for two observers (out of six) was violated in targets separated by two units, and an average number of 2 quantiles in three (out of 5) observers in targets separated by three units of distance.

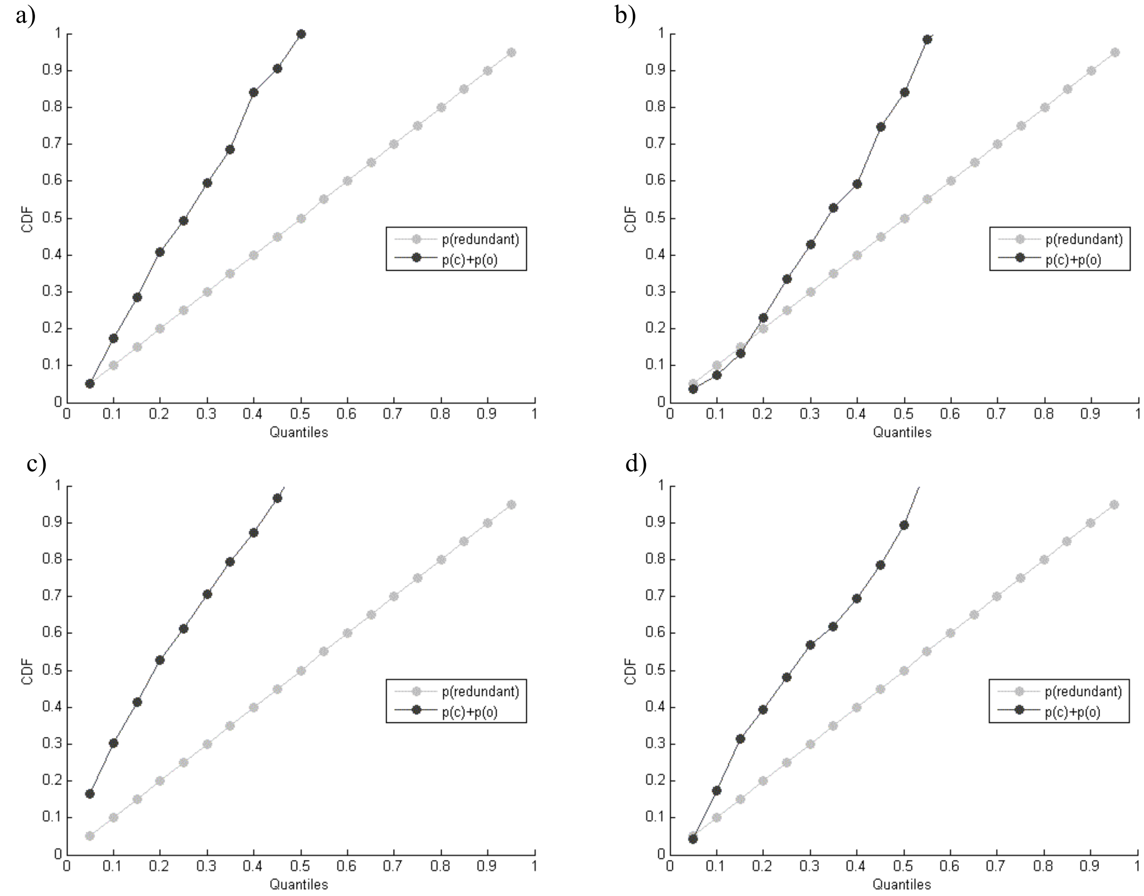

Figure 5.6. Results of the tests for violations of Miller's (1982) violation of the RMI in saccade latencies in the detection task of Experiment 1 including; violation of the RMI a) for all dual redundant targets, b) for dual redundant separated by one unit, c) for dual redundant separated by two units, d) for dual redundant separated by three units. The dark grey curve represents the cumulative probability function for the summed probabilities of RTs to single targets having occurred at a given time t; the light grey curve represents corresponding redundant target probabilities. Note that for the RMI to be satisfied, summed single dimension probabilities must be no smaller than redundant target probabilities.

Manual RTs in trials with eye movements were compared to trials without eye movements (see Table 5.14 for an overview of the results). Overall, manual RTs of trials with eye movements were significantly slower than those without eye movements ($t(12) = -5.66$, $p < .001$). Separate analysis of target-absent and present trials shows that this is true for target-absent ($t(12) = -7.84$, $p < .001$) and target-present trials ($t(11) = -5.21$, $p < .001$). Analysis of manual RTs (nine observers) in an ANVOVA with the factors eye movements (no eye movements, eye movements) and target definition (color, orientation, dual redundant) showed that both main effects were significant (eye movements: $F(1,8) = 22.45$, $MS_e = 303.81$, $p < .001$; target definition: $F(2,18) = 11.42$, $MS_e = 388.10$, $p < .001$); there was no significant interaction ($F(1.32,10.60) = 1.80$, $MS_e = 130.55$, $p > .05$). Multiple comparisons to follow-up the main effects revealed significantly faster target detection in trials without than with eye movements for all the three target definitions (color: *t*(8) = 3.13, *p* < .05; orientation: *t*(8) = 3.11, *p* < .05; redundant: *t*(8) = 5.53, *p* < .001). Furthermore, analogously to manual reaction times, orientation targets were detected significantly slower than color and dual redundant targets (respectively, *t*(8) = 3.58, *p* < .05 and *t*(8) = 3.62, *p* < .05).

Table 5.14

Mean manual RTs (and standard deviation) for trials with and without eye movements for each target dimension and distance. Because of the ten valid trials per condition, nine observers were included in dimensions analysis and five in the distance analysis.

Target type	Without eye movements	With eye movements
Color	378.60 (55.53)	400.76 (54.61)
Orientation	405.91 (57.89)	422.67 (59.12)
Redundant		
All	370.87 (48.76)	399.37 (50.23)
Distance 1	347.97 (55.92)	369.69 (53.61)
Distance 2	353.91 (56.38)	377.63 (44.03)
Distance 3	360.57 (60.00)	385.58 (55.71)

An ANOVA with the factors eye movements (no eye movements, eye movements) and distance (distances 1, 2, 3) (five observers) revealed significant main effects eye movements (*F*(1,4) = 14.59, MS_e = 283.32, *p* < .05) and distance (*F*(2,8) = 8.35, MS_e = 60.76, *p* < .05). There was no interaction between the factors (*F*(2,8) = .06, MS_e = 106.57, *p* < .05). Simple contrasts to follow-up the main effects revealed significantly or, respectively, marginally significantly faster target detection in trials without relative to without eye movements (color: *t*(4) = 6.79, *p* < .01; orientation: *t*(4) = 2.52, .05 < *p* < .10; redundant: *t*(4) = 2.51, .05 < *p* < .10). Furthermore, rts increased linearly with distance in general (*F*(1,4) = 19.40, MS_e = 52.32, *p* < .05) and both for trial without eye movements (*F*(1,4) = 5.28, MS_e = 75.31, *p* = .083) and with eye movements (*F*(1,4) = 5.95, MS_e = 106.13, *p* = .071). Interestingly, the latter result contradicted the overall manual RT analysis in which no systematic RT increase in function of the distance separating dual targets was found. In sum, this finding seems to suggest that removing trials with eye movements not directed toward the target from the analysis unveiled the distance effect observed by Krummenacher et al. (2002a). In turn, the findings suggest that observers in the Krummenacher et al. study avoided making eye movements (which is very likely as they were experienced observers [personal communication J. Krummenacher, 16 February 2010]). Note however, that the conclusion is based on a subset of five observers; a RT analysis without those critical trials did not show any significant effect ($F(2,20) = .11$, $MS_e = 72.36$, $p > .05$).

Landing sites of the first saccade following display onset in dual target trials was examined in terms of the two possibilities (fixation of either one of the dual targets vs. fixation in between targets) described in the introduction to Experiment 2. Based on the discussion of the global effect, it was suggested that saliency differences between the two dimensionally singly defined targets might modulate the fixation target. In order to statistically test this assumption, distances between the landing point of the first saccade and the center of both targets were computed to allow determining which of the two target items the saccade landed closer to. Based on the distance analysis, following the rationale of Miller and Lopes (1988) who assume that processing of visual dimensions follows individual preferences, the percentage of first saccades toward the color target was computed (given in column 2 of Table 5.15). In a next step, an index named the "strength of subjective saliency difference" for color and orientation targets defined by the difference between individual valid RTs for single color and orientation targets weighted by their pooled variance was computed (the value corresponds the a t-value, given in the third column of Table 5.15). This somewhat more complicated approach has the advantage (over the simple difference between mean RTs of both single target types) of taking into account the variability of individual RT distributions. In a next step, a linear regression was calculated between the strength of subjective saliency difference and the proportion of first fixations directed to the differently colored object of the dual target. The correlations statistically reliably predicted the proportion of color targets fixated first after display onset ($R = .81$, adjusted $R^2 = .61$, $F(1,9) = 16.58$, $MS_e = 65.78$, $p < .01$). The higher is the strength of the subjective salience discrepancy, the higher the probability that a color target is fixated in the first fixation after display onset. Note that if Participant 3 (who does not show a preference for either target dimension) is removed, the prediction becomes even better ($R = .92$, adjusted $R^2 = .84$, $F(1,8) = 43.12$, $MS_e = 30.01$, $p < .001$).

This result confirms the assumption that when the visual system is strongly biased toward the color targets, a saccade (in trials with eye movements) is directed to the color target in trials with dual color and orientation targets. How are landing sites distributed when the system has a less pronounced bias or no bias at all? According to Findlay (1997), who found that saccades are directed to the location of the object with the higher saliency if object size differs and to the center of gravity of two objects if they are equally salient, and further assuming that objects defined on different dimensions generate equal saliency signals and that neither of the dimensions is preferred, the nearest target should be selected. Consequently, the smaller the strength of the subjective saliency difference, the larger proportion the proportion of trials in which the nearest target item should grow. To test this assumption, a linear regression was run under the predicting of a significant negative influence of the strength of the subjective saliency difference on the proportion of selected nearest target items; the prediction was confirmed in a significant regression ($R = .68$, adjusted $R^2 = .41$, $\mathrm{MS_e} = 48.55$, $F(1,9) = 7.92$, $p < .05$).

Table 5.15

Values per participant for the analysis of the first selected targets in dual redundant target trials. The second column presents the value for the subjective saliency difference strength between color and orientation targets (difference between RTs for color and orientation weighted by their pooled variance, corresponds to a t-value). The third column displays the percentage of saccades toward a color target, whereas the last column presents the percent of saccades toward the nearer target. Because usable trials number varied from observers, all distances were collapsed together.

Participants	Saliency difference strength	Saccades toward color targets (%)	Saccades toward the near target (%)
7	-0.94	42.31	84.62
5	1.82	46.88	75.00
11	2.52	57.41	70.37
6	2.82	57.75	71.36
4	3.56	56.67	80.00
10	4.08	74.89	61.64
3	4.88	50.79	77.78
2	4.93	70.00	75.00
8	4.98	78.39	59.80
9	6.01	76.14	56.82
1	6.06	75.28	62.92
Mean	3.70	62.41	70.48

5.4.3. Comparison of single and dual redundant target trials

The main goals of Experiment 2 were to replicate Krummenacher et al.'s (2002a) manual RTs results demonstrating that parallel co-active feature processing is location-specific, and to investigate if results similar to those obtained in manual RTs would also be observed in oculomotor parameters. Table 5.13 summarizes manual and oculomotor results of Experiment 2. The manual RT analyses failed to fully replicate Krummenacher et al.'s findings.

Experimental conditions (single vs. dual redundant targets) and target definitions (color, orientation, redundant) were compared in a two-way repeated-measures ANOVA. The ANOVA revealed a significant main effect of target definition ($F(1.23,12.25) = 25.64$, $MS_e = 614.62$, $p < .001$; Huynh-Feldt-corrected degrees of freedom), conditions did not differ statistically significantly, however, ($F(1,10) = 1.66$, $MS_e = 1153.97$, $p > .05$), the interaction was not significant, either, ($F(2,20) = .91$, $MS_e = 45.89$, $p > .05$). As in the separate analyses of the two conditions, simple contrasts revealed that RTs to redundant ($M = 397.9$ ms, $SD = 56.6$ ms) and color targets ($M = 402.94$ ms, $SD = 54.86$ ms) were significantly faster than to orientation targets ($M = 436.4$ ms, $SD = 71.5$ ms; respectively, $t(10) = 4.57$, $p < .01$ and $t(10) = 5.89$, $p < .001$).

Single and dual redundant targets differed in terms of oculomotor parameters. No difference was observed for target definition (color, orientation, redundant) or condition (single redundant, dual redundant) for number of fixations (conditions: $F(1,6) = .78$, $MS_e = .01$, $p > .10$; dimensions: $F(2,12) = 2.40$, $MS_e = .003$, $p > .05$; interaction: $F(2,12) = 1.92$, $MS_e = .001$, $p > .10$) and number of saccades (conditions: $F(1,6) = .83$, $MS_e = .004$, $p > 10$; dimensions: $F(2,12) = 2.12$, $p > .05$, $MS_e = .002$; interaction: $F(2,12) = 3.18$, $MS_e = .001$, $p > .10$). First saccade latencies and landing errors, [as well as inspection time] differed significantly between conditions. The saccade latency analysis showed a significant main effect of target definition ($F(1.21,7.25) = 14.26$, $MS_e = 219.13$, $p < .01$) and a significant interaction ($F(2,12) = 7.85$, $MS_e = 62.28$, $p < .01$), whereas the main effect of the condition was tendentially significant ($F(1,6) = 4.64$, $MS_e = 434.49$, $.05 < p < .10$). The interaction effect was due to a significant difference between single (204.9 ms, $SD = 26.5$ ms) and dual redundant targets ($M = 231.6$ ms, $SD = 27.1$ ms; $t(7) = 4.47$, $p < .05$). A close look at the distance effect ($F(1.51,9.07) = 18.88$, $MS_e = 149.93$, $p < .001$; Huynh-Feldt-corrected degrees of freedom) indicated that saccade latencies to single redundant targets were significantly smaller than to dual redundant targets for each distance level (D1: $t(6) = -4.17$, $p < .05$; D2: $t(6) = -4.54$, $p < .05$; D3: $t(6) = -5.18$, $p < .05$). However, the distance levels did not differ significantly from each other (D1-D2: $t(6) = -3.11$, $p > .10$; D1-D3: $t(6) = -1.63$, $p >.10$; D2-D3: $t(6) = 2.18$, $p >.10$).

Further, landing sites of the first fixation after display onset were marginally closer in redundant target trials ($M = 32.4$ pixels, $SD = 5.5$ pixels) than in color target trials ($M = 36.5$ pixels, $SD = 4.9$ pixels, $t(6) = 2.89$, $.05 < p < .10$), they were significantly ($t(6) = 3.6$, $p < .05$) closer than in orientation target trials ($M = 39.1$ pixel, $SD = 6.6$; main effect of target definition: $F(2,12) = 9.72$, $MS_e = 16.60$, $p < .01$). No significant main effect of condition was observed ($F(1,6) = .309$, $MS_e = 32.54$, $p > .10$). The interaction did not reach statistical significance ($F(2,12) = 1.43$, $MS_e = 14.85$, $p > .10$), and simple contrasts following-up potential differences between conditions on the level of individual dimensions revealed only a significant difference between single ($M = 34.8$ pixels, $SD = 7.3$ pixels) and dual redundant targets ($M = 30.0$ pixels, $SD = 4.2$ pixels, $t(6) = 2.87$, $p < .05$).

An analysis of the distance between dual redundant targets ($F(3,18) = 18.44$, $p < .001$, $MS_e = 22.69$) showed that saccades directed at dual redundant targets separated by one unit ($M = 22.8$ pixels, $SD = 3.4$ pixels) landed significantly nearer to one of both targets than single ($M = 34.8$ pixels, $SD = 7.3$ pixels; $t(6) = 5.5$, $p < .01$) and dual redundant targets separated by three units ($M = 40.63$ pixels, $SD = 6.83$ pixels; $t(6) = 7.59$, $p < .001$). All other comparisons were not significant (all $p < .10$). [Moreover, although no significant differences between target definitions were observed ($F(2,12) = 1.46$, $MS_e = 5.06$, $p > .10$), observers spent more time visually inspecting the search display in the dual ($M = 64.6$ %, $SD = 5.7$ %) than in single redundant target displays ($M = 62.3$ %, $SD = 5.7$ %, $F(1,6) = 11.49$, $MS_e = 4.67$, $p < .05$). This main effect was only due to the significant difference between single ($M = 61.3$ %, $SD = 6.7$ %) and dual redundant target displays ($M = 67.1$ %, $SD = 5.5$ %, $t(6) = -4.18$, $p < .05$). Further, a repeated measure ANOVA reveled a significant main effect of the distance between features ($F(3,18 = 14.67$, $MS_e = 4.67$, $p < .001$); Multiple comparisons showed that inspection time in trials with single redundant targets was significantly shorter than in trials with dual redundant targets separated by one ($M = 66.6$ %, $SD = 5.8$ %, $t(6) = -4.42$, $p < .05$) and two units of distance ($M = 68.8$ %, $SD = 5.4$ %, $t(6) = -5.97$, $p < .01$); displays with dual targets separated by three distance units ($M = 66.1$ %, $SD = 5$ %) did not differ significantly from all other conditions (all $t(6) < 3.22$, $p < .10$).]

Due to the criterion of a minimum of ten valid trials per condition, three observers were included in the analysis comparing manual RTs between trials with and without eye movements during the display onset. For this reason, no statistical tests were conducted on the comparison between trials with and without eye movements and their effect on manual RTs. However, a descriptive analysis showed constantly higher RTs for trials with compared to trials without eye movements (see Tables 5.10 and 5.14 above).

5.4.4. Discussion

Although Experiment 2 failed to fully replicate Krummenacher et al.'s (2002a) manual RTs results, in which reaction times for dual targets increased with distance, an analysis of Miller's (1982) Race Model Inequality at an individual level revealed consistent trends toward a parallel co-active processing in dual redundant trials in which dual target items were presented at spatially close locations. Further, single and dual redundant targets sessions differed in function of their RTs. Comparison of oculomotor parameters between the two conditions revealed that single redundant targets generated shorter first saccade latencies than dual redundant targets (independently of the distance) the first saccade landed closer to the target in trials with dual redundant targets than in trials with single targets. Moreover, although no significant violations of Miller's (1982) RMI for the latencies of the first saccade were observed, analysis at an individual level suggested parallel co-active processing in function of the distance between dual target distances; the closer the targets, the higher the number of individual numerical violations was.

Taken together, these results support the assumption that a saccadic saliency map controlling eye movements operates on the same principle as the saliency map thought to control attention allocation. Overall saliency is based on relative object saliency in the visual field and a saccade is executed toward the object whose saliency signal exceeds a threshold. In single redundant target trials, because both features are located at the same position, a target generates a strong unique saliency signal, whereas in dual redundant target trials, two separate saliency signals, at slightly different spatial locations, are generated and the overall saliency activation takes more time to exceed a threshold. The stronger the signal, the faster the threshold is exceed as reflected in shorter saccade latencies. If, as suggested by Experiment 1, saccades in detection task constitute an additional processing step confirming target presence, a single redundant target, by the strength of its salience signal, might confirmatory foveation less frequently or less precisely that single targets with weaker saliency signals. The presence of multiple (two) salient objects in the visual field could have forced the visual system make a selection of one target. In the present Experiment 2, the selection was biased in function of the strength of the subjective saliency difference between the two target types. Indeed, when the visual system was strongly tuned to color objects, the probability to select a color target was larger, whereas, when the visual system was less biased, the probability to select the nearest, rather than an object defined on a particular dimension or by a particular feature was observed. The selection of the first target to be fixated in dual redundant target displays turns out to be mainly saliency-based.

5.5. General discussion

The present paper was aimed at investigating whether the control of the oculomotor system relies on mechanisms based on a spatial summation of dimension-based saliency signals as proposed in the orientation of attention (e.g., Wolfe, 1994). Furthermore, the strategies applied by observers to perform visual search tasks with different instructions were examined via eye movement frequencies. In Experiment 1, it was shown that the identification of a conjunction target implicates more frequent eye movements compared to the detection of a singleton feature object. Nevertheless, saccades are not constantly used in a conjunction task, suggesting that fixating the target is not a necessary condition to solve this task. Furthermore, making a saccade towards the target location is associated with a clear increase of manual RTs (in both tasks).

Despite these costs and although observers are well able to use strategies in order to solve a detection task without making any saccades, in a conjunction search suppressing saccades seems to be essentially more difficult. This suggests that according to task requirements there are different functional uses of saccades. In conjunction tasks, a target fixation can facilitate the access of the feature level and the integration of multiple features across dimensions that are necessary to solve the task adequately. In contrast, in detection tasks, an eye movement towards the target merely serves as a confirmation of target presence, which at this time already is detected by the attention system.

However, further research is required to determine whether saccades to the target primarily contribute to an increase in sensitivity at the fixated location or whether they support inhibition of non-targets next to the target location. Using displays containing only the target item would contribute to differentiating between these possibilities.

Although detection tasks of Experiment 1 and 2 failed to fully replicate previous findings at a behavioral level, their results support the assumption of a spatial saliency summation. They report RT redundancy gains and violations of the Race Model Inequality in latencies of saccades to dimensionally redundantly relative to singly defined targets. These findings suggest that the saliency signal controlling the saccade elicitation operates according to similar functional principles than the saliency signal monitoring the deployment of focal attention. Functionally, saccadic saliency signals are generated separately for a limited number of dimensions and put into a consecutive processing module in a co-active fashion (as supported by RMI violations) that is involved in the generation of the saccadic saliency map. Due to the summation of the saliency signals in this module, a redundantly defined target will generate a saliency peak that exceeds faster the threshold responsible for the elicitation of a saccade (as compared to a singly defined target).

These assumptions were confirmed in Experiment 2 demonstrating that a spatial summation of saliency signals on the saccadic saliency map seems to depend of the distance between features, as observed in behavioral studies (Krummenacher et al., 2002a). Only a spatial overlap of both features in the redundant target condition (i.e., a single rather than two separate target items) expedites saccadic latencies and generates clear violations of the RMI. When both features were physically separated, redundancy gains for saccadic latencies were abolished and the number of individual violations of the RMI diminishes as a function of the distance between features.

Additional support in favor of a saliency-based control of eye movements can be found in oculomotor parameters of dual redundant targets in Experiment 2. An analysis of the preferentially selected target during dual redundant targets led to assume that the selection process is based on the subjective saliency of both dimensions. When the (individual) visual system was strongly biased toward color, color targets were largely preferred to orientation targets, whereas a less biased system seemed to select the nearest target.

However, this “default”, exogenous control mode can be modulated by task requirements. The manual response time to redundantly defined targets is faster when the target has to be detected (detection task of Experiment 1) compared to when it has to be identified (conjunction task of Experiment 1), reflecting deeper processing that then is required to solve the conjunction task adequately. By contrast, saccades in conjunction tasks were executed faster and landed closer to the target compared to saccades in detection tasks. This finding suggests that higher accuracy can be provoked by endogenous factors. Note that targets are physically identical in both tasks, but that the conjunction task seems to require an accurate target fixation. Therefore the (bottom-up) visual information available is modulated in such a way as to allow more accurate saccades to be programmed in a briefer amount of time.

Although until now, no latency shortening for endogenous saccades seem to be reported in the literature, the present results do not contradict previous observations of increased preparation time required for endogenous saccades as will be described in the following section.

Studies using an anti-saccade paradigm (e.g., Hallett, 1978), in which observers had to make a saccade to the opposite direction of the target location, found longer latencies in the anti-saccade condition than in the pro-saccade condition (i.e., when a saccade has to be directed towards the target), suggesting that an endogenous saccade requires more time to be programmed adequately. Similar results were observed in oculomotor capture tasks, in which participants had to fixate a singleton target embedded in a search array. In some trials, an irrelevant singleton item was presented simultaneously with the target. Van Zoest, Donk and Theeuwes (2004) reported that the saccades directed towards the task-irrelevant singleton item had shorter latencies than the saccades to the target. These findings support the assumption that exogenous saccades (i.e., saccades toward the task-irrelevant object) are faster executed than endogenous saccades.

Furthermore, Shepherd, Findlay and Hockey (1986) demonstrated that saccade latencies are modulated by endogenous cues. In one experimental condition, observers were instructed to make a saccade toward the target that appeared either to the left or to the right of the fixation cross. The target was preceded by an endogenous cue (i.e., an arrow) indicating the possible target location with a certain degree of confidence (depending on the condition). They remarked that the latency for the first saccade was lengthened when the cued location did not correspond to the target location. These enlarged latencies can be explained by the incongruence of the attentional and oculomotor foci generated by unreliable cues.

Taken together, in previous paradigms, the natural process of saccade generation is counteracted (either with an unusual saccade direction in an anti-saccade task, or the presence of a task-irrelevant object in an oculomotor capture task, or the mismatch between attentional and ocular foci in a cueing paradigm) that required a strict control of the saccade program. In other words, these tasks required an inhibition of the stimulus-driven saccades generation. On the other hand, in the conjunction task of Experiment 1, saccade triggering was facilitated because of the convergence of stimulus- and goal-driven purposes. The difference between these types of tasks can be found in the interaction between display features and task requirements; if they match, latencies are expedited, if they do not, latency costs arise.

6. Effect of practice on feature processing in visual search task: clear evidence of a parallel co-active processing needs some familiarity with the task to emerge

6.1. Abstract

Recently, it has been demonstrated (e.g., Poom, 2009) that redundantly defined objects do not necessarily violate Miller's (1982) race model inequality (RMI). The present study investigates whether the difficulty to observe violations of the RMI might be due to a lack of task familiarity. Therefore naïve observers were tested in a feature detection task in which targets could be singly and redundantly defined. Each observer performed four sessions within a week. The results show that practice improved the detection of any target type. Furthermore, violations of the RMI magnitude also increased with the number of sessions. This study therefore supports the claim that visual features are processed according to a parallel co-active model (e.g., Miller, 1982).

6.2. Introduction

Recent studies on visual search (Krummenacher, Müller & Heller, 2001, 2002a, b) have demonstrated that a target object defined by redundant visual dimensions (color and orientation) surrounded by homogenous non-target objects (i.e., a red horizontal bar among green vertical bars) are detected faster than targets defined by a single dimension (i.e., a red vertical bar among green vertical bar). This expedited response to redundantly defined targets was termed as redundancy gains.

Two models were proposed to explain this speeded reaction for redundantly defined targets, the first assumes that redundancy gains are due to "statistical facilitation" arising as a result of a parallel race of independent signals to trigger a response (race model; Raab, 1962), whereas a second, alternative account assumes that independent signals feed into a common module that triggers the response. In contrast to a parallel race, both signals contribute to the activation of the response, thus the term "co-active activation" model (Miller, 1982). Miller proposed a method for differentiating parallel race and parallel co-active models. Although both models assume that signals are processed independently and in parallel, they diverge concerning the mechanisms which generate a response. The parallel race model assumes that the response indicating the presence of a target is triggered after one of the signals exceeds a threshold required to trigger the response. Assuming that the reaction time distributions of the single signals overlap and that the faster of the two signals triggers the response, reaction times for redundantly defined objects are *on average* faster than expected based on the reaction time distributions for singly defined targets.

Miller (1982) suggests that the response is generated from the summation of the processing activation of both feature signals. When this activation accumulation exceeds a certain amount, the answer is triggered. He proved that all models postulating a strict parallel processing between features, as the Race Model (Raab, 1962), do not violate the following inequality: $F_R(t) \leq F_{T1}(t)+ F_{T2}(t)$, where t is the time since display onset and F the cumulative function of the reaction times. T1 and T2 correspond to features composing the redundantly defined object R. Violations of this inequality (labeled as race model inequality) give therefore evidence against a strict parallel processing. Using Miller's race model inequality, Krummenacher et al. (Krummenacher, Müller & Heller, 2001, 2002a) showed that redundancy gains for visual feature signals (color and orientation) are generated according to a parallel co-active processing, namely the cumulated activation of both features is responsible for the response triggering. In other words, the target detection seems to stem from the integration of visual feature signals.

However, a recent study failed to replicate these findings (Poom, 2009). One plausible explanation for this outcome is that participants did not have enough practice with the task to provide clear evidence in favor of a parallel co-active processing. Poom's (2009) results are established on the base of a small number of trials (about 80), whereas Krummenacher et al.'s (2001, 2002a, 2002b) participants performed at least 400 trials.

Performance improvement through practice can be observed in daily life. For example, a secretary needs probably more than one lesson in order to be able to type quickly and without looking at the keyboard, and a tennis champion has an incredibly large number of training hours behind him to have reached her/his actual performance level, like an ornithologist to distinguish birds. In vision research, practice enhances discrimination of visual objects or characteristics, as vernier offsets (e.g., Fahle, 2004; McKee & Westheimer, 1978), Gabor patches (e.g., Lu, Chu, Dosher & Lee, 2005; Schoups, Vogels & Orban, 1995), texture orientation (e.g., Karni & Sagi, 1991, 1993), contrast (e.g., Adini, Wilkonsky, Haspel, Tsodyks & Sagi, 2004; Chung, Levi & Li, 2006; Sowden, Rose & Davies, 2002), depth in random dot stereograms (e.g., Gantz, Patel, Chung & Harwerth, 2007) or motion direction (e.g., Lu, Chu & Dosher, 2006). The increasing ability to pick up more and more information from the environment through practice was termed perceptual learning (Gibson, 1969).

The improvement of performance through practice can also be observed in visual search tasks. In such tasks (e.g., Treisman & Gelade, 1980) it is usually found that the detection time of a singleton feature target (e.g., a red vertical bar among green vertical bar) is unaffected by the number of distractor objects (feature detection task). However, the time required to detect a target defined by its unique combination of features (i.e., a red vertical bar among red horizontal bars and green vertical bars) increases with the number of distractors in the search display (feature conjunction task). According to these results, it has been proposed that, in the feature detection task, all the objects in the visual scene can be processed simultaneously (parallel search), while in the feature conjunction task, each object (or group of objects) has to be scanned to solve the task (serial search). Similar results were obtained in studies involving tasks presenting a search asymmetry (e.g., Treisman & Gormican, 1988). Search asymmetry refers to the observation that a stimulus A (i.e., a circle with the vertical line) is faster detected among stimuli B (i.e., plain circles) than a stimuli B among stimuli A. Similarly to a feature detection task, a target A among distractors can be found via a parallel search, whereas a target B among distractors A requires a serial search to be found.

Ahissar and Hochstein (1997) found that practice benefits depended on the difficulty of the task. In a feature search task, the detection of the target improved faster when the display stayed visible until an answer was given (easy task) than when the display onset was followed by a mask (hard task). Furthermore, the distinction between serial and parallel search observed in asymmetrical search tasks can be abolished within two days of practice (Sireteanu & Rettenbach, 1995). Krummenacher et al. (2002b, Exp. 2) investigated whether practice can improve search performance for redundantly defined targets in a complex search task. Participants not only had to search for an odd target object (defined either by a single dimension – color or orientation - , or by a combination of two dimensions – color and orientation) but also had to report the direction of the dial placed in it. Distractor objects contained also a dial whose direction was randomly assigned. The experiment was divided into 3 sessions. They observed an overall decrease in RTs, accompanied by an increase in redundancy gains over the sessions, that is, in the first session they observed no redundancy gains, whereas in the last session significant redundancy gains were observed. This result suggests that, even if the target dimension is irrelevant for the response selection (linked to the orientation of the dial), practice can improve RTs for redundantly defined targets in difficult visual search tasks. However, against expectation, redundantly defined targets did engender no reliable violation of RMI.

These previous studies provide evidence that practice can improve performance in visual search. The present study was aimed at investigating whether the lack of violations of the RMI reported by Poom (2009) for targets defined by color and orientation can be attributed to a lack of practice. According to Krummenacher et al. (2002b), practice might reduce RTs in general and augment the speed difference between singly and redundantly defined targets, namely the redundancy gain should increase through sessions. Finally, more violations of the RMI should be observed in the last compared to the first session.

6.3. Method

Participants. Thirteen naïve observers (twelve female and one male) took part in this experiment. All were students at the University of Fribourg. They received 8 course credits. They were aged between 19 and 27 years (median = 20). All observers had normal or correct-to-normal vision, including normal color vision.

Stimuli. Visual stimuli were 49 green vertical bars (RGB: 0, 200, 0) subtending 0.38° x 1.15° of visual angle presented on a black background (RGB: 0, 0, 0). Colors were roughly isoluminant. The bars were displayed in a virtual 7x7 matrix, subtending 13.56° x 14.25° of visual angle. The position of each item in its matrix cell was randomly jittered for each trial (0.19° along the horizontal and vertical axes, respectively to the cell array centre) to prevent colinearities with the other stimuli. The target bar could be defined either by one feature (color or orientation) or by two features (color and orientation). In a color condition, the target was either red (RGB: 255, 0, 0) or blue (RGB: 0, 0, 255), and in the orientation condition, the bar was either tilted 45° to the left or to the right. In the redundant condition the target was a combination of a color and an orientation.

Procedure and design. The experiment was composed of four identical sessions which had to be completed on four different days within one week. At the beginning of each session, participants were instructed to press as fast and with as few errors as possible the left Ctrl key when no target bar was present and the right Ctrl key when a target bar was present. These instructions were not only presented on the screen at the beginning of each warm-up block but also orally given by the investigator. In each session, participants had to complete 1 warm-up block of 20 trials (8 with no target, 4 with a color target, 4 with an orientation target, and 4 with a redundantly defined target) and 15 experimental blocks of 40 randomly presented trials. Each block contained 16 trials without a target and 8 of each other condition (4 red and 4 blue targets, 4 left- and 4 right-tilted targets, and 2 of each possible combination of both features). The whole experiment took about 30 minutes to be completed. Each trial began with a fixation cross presented in the middle of the monitor for 500 ms, followed by a blank of 500 ms. The display was presented until a response was given by the participants. The stimulus array was followed by a second blank of 1000ms. During the exercise block, a visual feedback was given for 800ms between the search display and the second blank.

*Apparatus and setting***.** Participants seated at a distance of approximately 60 cm from a Philipps Brilliance P202 monitor controlled by a HP Compaq Business Ultra Slim Desktop Dc7600 personal computer (Pentium IV at 3.2 GHz, 512 Mb RAM). The monitor resolution was set at 1280 x 1024 Pixels and its refresh rate at 100Hz. This experiment was realized using Cogent 2000 developed by the Cogent 2000 team at the FIL and the ICN and Cogent Graphics developed by John Romaya at the LON at the Wellcome Department of Imaging Neuroscience. The experiment was conducted in a darkened room.

Data analysis. Incorrect responses were discarded from analyses. To avoid anticipatory and extreme slow responses the RTs smaller than 200 ms and bigger than 1200 ms were excluded (the latter) [7]. Additionally, for each participant RTs which were more than 3 standard deviations away from the mean of each condition were removed. Finally, only participants having less than ten percent unusable trials in each session were included (eight out of thirteen). The overall procedure discarded 5.58 % of the remaining data.

Error rates differed significantly between target type (i.e., color, orientation and redundantly defined targets; $F(1.06,7.42) = 28.63$, $MS_e = 2.46$, $p < .001$). Multiple comparisons revealed that participants missed significantly more orientation targets ($M = 5.05$ %, $SD = 3.02$ %) than color targets ($M = 1.54$ %, $SD = 2.05$ %; $t(7) = 5.54$, $p < .01$) and redundantly defined targets

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[7] This limit was chosen depending on the overall reaction time distribution.

(*M* = 1.12 %, *SD* = 1.68 %; *t*(7) = 5.30, *p* < .01). Further, marginally less errors were made in redundant than in color trials (*t*(7) = .2.65, *p* = .099). This result suggests that redundant targets (marginally less missed than color targets) were easier detectable for naïve participants than color and orientation targets. Finally, reported multiple comparisons were adjusted with Bonferroni correction if necessary.

6.4. Results

The results are reported in two parts. In a first step, an overall data analysis will be presented, containing the manual RT analysis on target dimensions, the redundancy gain test and the RT distribution analysis. In a second step, these analyses are split by session and compared with each other to examine if learning is possible in a pop-out detection task. Results for RTs and redundancy gain analyses are presented in Table 6.1.

Overall analysis

RTs. A one-factor repeated measure analysis of variance (ANOVA) with the factor target type showed a significant effect of the target type (*F*(2,14) = 34.25, MS_e = 155.30, *p* < .001). Simple effects revealed that redundant targets (*M* = 445.7 ms, *SD* = 56.7 ms) were significantly faster detected than color (*M* = 457.2 ms, *SD* = 60.3 ms) and orientation targets (*M* = 495 ms, *SD* = 63.5 ms; *t*(7) = 3.23, *p* < .05 and *t*(7) = 6.5, *p* < .01, respectively), and color targets were faster detected than orientation targets (*t*(7) = 5.55, *p* < .01; see first column, Table 6.1). Furthermore, the redundant targets were detected 30.3 ms faster than the average of the single targets: Gain $_{\mathrm{Av}}$, *t*(7) = 6.27, *p* < .001. The result that mean overall RTs to color targets are faster than to orientation trials might suggest that all the observers' RTs to color targets are faster, namely, that there is a fixed-favored feature or dimension (see Biederman & Checkosky, 1970). If redundancy gains are tested under the fixed-favored dimension assumption, a significant redundancy gain of 11.4 ms for redundant compared to color targets was reported (Gain $_{\mathrm{B\&C}}$; *t*(7) = 3.29, *p* < .05. The fixed-favored feature assumption, however, is not necessarily correct, as observers might prefer different dimensions or dimension at all. Miller and Lopes (1988) proposed an alternative procedure avoiding over- or underestimation of the redundancy gains; mean RTs of the single target conditions are compared for each observer individually. If they differ significantly (according to a liberal criterion of α = .10), the faster RT is used for comparison; if not, the overall mean RTs from the two features is preferred. The retained estimate is then compared with the mean RTs of the redundantly defined targets for each observer. With this procedure, the estimated redundancy gains for the entire experiment was 12 ms (Gain $_{M\&L}$; $t(7) = 3.06$, $p < .05$, see Table 6.1).

Table 6.1

Mean value (and standard deviation) for each target type and redundancy gain procedure for the whole experiment and in each session.

Target type	Overall	Session 1	Session 2	Session 3	Session 4
Absent	535.60 (65.10)	592.31 (65.52)	523.45 (58.42)	517.41 (77.29)	508.69 (73.80)
Color	457.16 (60.32)	495.63 (51.32)	445.39 (52.16)	447.24 (73.84)	440.07 (78.19)
Orientation	495.01 (63.49)	529.32 (51.83)	488.49 (58.43)	488.81 (71.77)	472.35 (84.45)
Redundant	445.75 (56.73)	480.70 (55.03)	439.54 (46.24)	434.40 (66.77)	428.31 (75.97)
Redundancy gain					
Gain $_{M\&L}$	11.97 (11.97)	15.53 (21.63)	6.90 (13.39)	15.12 (13.45)	12.96 (11.72)
Gain $_{Av}$	30.34 (13.68)	31.78 (30.46)	27.41 (14.56)	33.63 (9.28)	27.90 (12.59)
Gain $_{B\&C}$	11.41 (10.00)	14.93 (22.97)	5.85 (11.02)	12.85 (11.25)	11.76 (12.00)

Note. Mean RT redundancy gains are relative to the fastest single-feature (Gain $_{B\&C}$ and Gain $_{M\&L}$) and relative to the average of both single feature targets (Gain $_{Av}$). $_{B\&C}$ = Biederman and Checkosky, 1970; $_{M\&L}$ = Miller and Lopes, 1988.

RT distributions. According to Miller (1982), a RT distribution analysis allows differentiating a parallel co-active processing from a strict parallel processing for a redundantly defined target. As mentioned above, he proved that all models postulating a strict parallel processing do not violate the Race Model Inequality. This inequality is violated when, at a certain time *t*, the probability to trigger a response for a redundantly defined (color & orientation) target is larger than the summed probability to trigger a response for a target defined by color or orientation (singleton feature target). In order to compare observers, RT distributions are expressed in quantiles (i.e., the 5th, 10th, etc., percentiles). Because Krummenacher et al. (2001, 2002a, b) demonstrated evidence for parallel co-active architecture underlying processing of dimensional signals in visual search for singleton feature targets, cumulative probability functions for redundantly defined targets and summed probability functions of single targets at each quantile are compared using one-tailed t-tests.

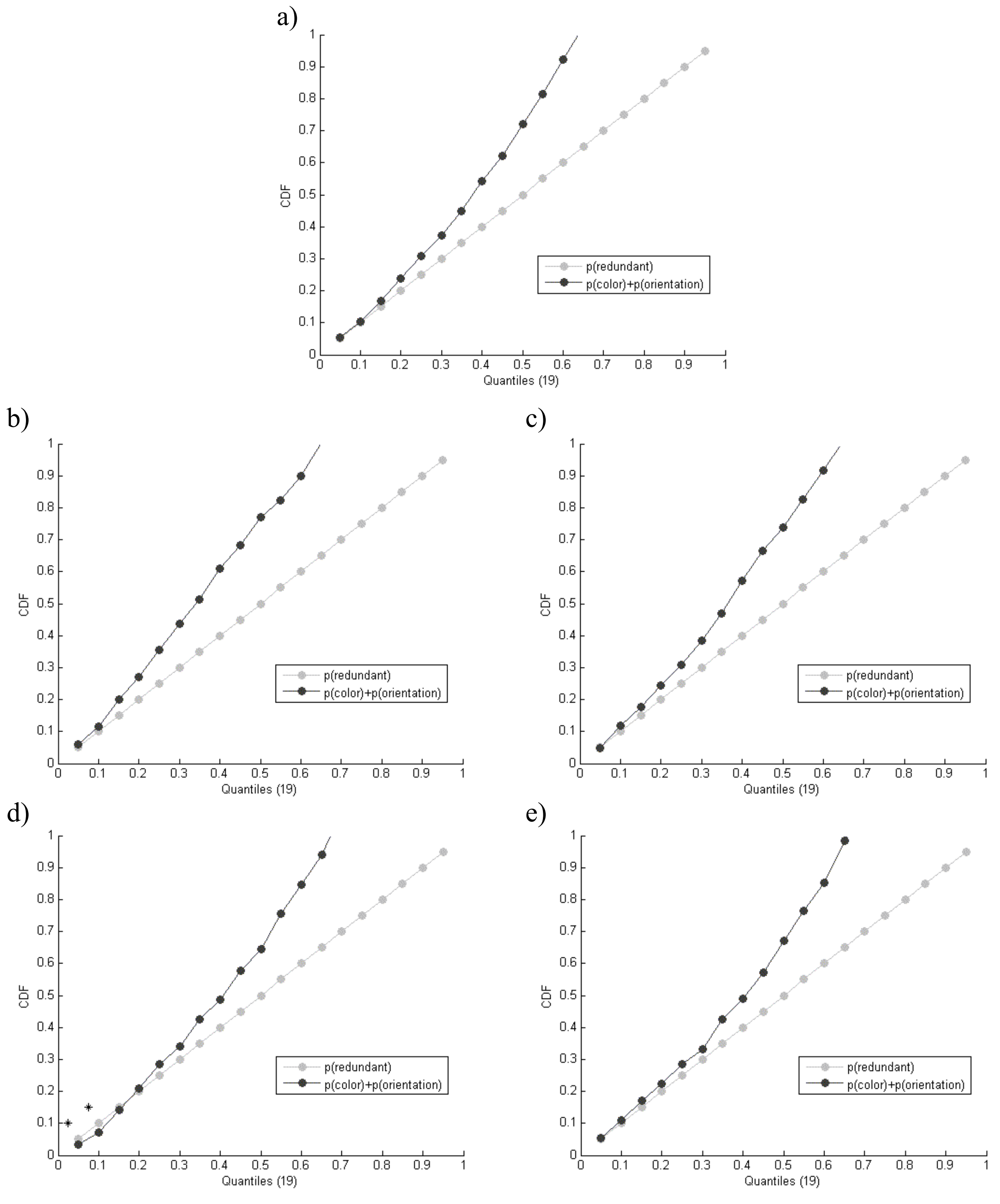

Figure 6.1. Results of the tests for violations of Miller's (1982) RMI for the entire experiment (panel a), and for session 1 to 4 (panels b to e). The dark grey curve represents the cumulative probability function for the summed probabilities of RTs to single targets having occurred at a given time t (in order to compare between participants, the x-axis represents the cumulative function for the redundant targets instead of time, see text for more details); the light grey curve represents corresponding redundant target probabilities. Note that for the RMI to be satisfied, summed single dimension probabilities must be no smaller than redundant target probabilities. Stars indicated significant violations of the RMI ($p < .05$).

As illustrated in Figure 6.1 (panel a), RT distribution analysis for the entire experiment did not show significant violations of the RMI. At an individual descriptive level, five participants presented individual violations of the RMI at 2.4 quantiles on average (range from 1 to 4 quantiles). This descriptive result gave some indication that color and orientation were somehow processed in a parallel co-active way in more than half of the participants.

Session analysis

In this section, results for each session are described in the same way as in the previous section, and are compared with each other in a subsequent section dedicated to practice effects. Moreover, due to their more adequate estimation of the redundancy gains, only redundancy gains from Miller and Lopes' (1988) procedure are reported.

In the first session, a one-factor repeated measures ANOVA showed a significant effect of Target Type ($F(2,14) = 9.54$, $MS_e = 155.23$, $p < .01$). Multiple comparisons showed no significant difference between redundant ($M = 480.7$ ms, $SD = 55$ ms) and color target types ($M = 495.6$ ms, $SD = 51.3$ ms *;* $t(7) = 1.84$, $p < .10$), but between the color and orientation ($M = 529.3$, $SD = 51.8$ ms) target types ($t(7) = 3.28$, $p > .05$), as well as between the orientation and redundant target types ($t(7) = 3.19$, $p > .05$). Furthermore, the outcome of the Miller and Lopes' procedure revealed only a marginal redundancy gain of 15.53 ms ($t(7) = 2.03$, $p = .082$). Finally, no significant violations of the RMI were observed (see Figure 6.1, panel b). At an individual descriptive level, an average of 4.75 quantiles (range from 1 to 6 quantiles) presented higher cumulative functions for redundant targets in four participants.

In the second session similar results could be observed compared to the first session. A one-repeated measure ANOVA showed a significant effect of Target Type ($F(2,14) = 31.87$, $MS_e = 179.43$, $p < .001$). Multiple comparisons revealed a marginally significant difference in the detection of redundant ($M = 439.5$ ms, $SD = 46.2$ ms) and color targets ($M = 445.4$ ms, $SD = 52.2$ ms; $t(7) = 1.50$, $p = .083$), while orientation targets ($M = 488.5$ ms, $SD = 58.4$ ms) were detected significantly slower than redundant ($t(7) = 6.07$, $p < .01$) and color targets ($t(7) = 5.84$, $p < .01$). Moreover, neither a significant redundancy gain was observed ($M = 6.9$ ms, $SD = 13.4$ ms), $t(7) = 1.45$, $p > .05$), nor a significant violation of the RMI was observed (see Figure 6.1, panel c). However, at an individual level, five participants presented RMI violations at on average 3.2 quantiles (range from 1 to 6).

In the third session, a one-factor repeated measures ANOVA showed a significant main effect of the target type (*F*(1.26,8.81) = 28.85, MS$_e$ = 356.76, *p* < .001; Huynh-Feldt-corrected degrees of freedom). Multiple comparisons revealed significantly faster RTs for redundant targets (*M* = 434.4 ms, *SD* = 66.8 ms) than for color (*M* = 447.2 ms, *SD* = 73.8 ms) and orientation targets (*M* = 488.8 ms, *SD* = 71.8 ms; *t*(7) = 3.23, *p* < .05 and *t*(7) = 7.36, *p* < .001, erspectively) and color targets were faster detected than orientation targets (*t*(7) = 4.20, *p* < .05). Moreover, a significant redundancy gain (15.1 ms) was observed; *t*(7) = 3.18, *p* < .05. RT distributions analysis reported two significant violations of the RMI at quantile 5 (*t*(7) = 3.5, *p* < .001) and 10 (*t*(7) = 4.98, *p* < .001; see Figure 6.1, panel d). Furthermore, at an individual level, RMI was violated on average in 3.75 quantiles (range from 2 to 5) in the entire sample.

Finally, as in previous sessions, a one-factor repeated measures ANOVA reported a significant main effect of the target type in Session 4 (*F*(2,14) = 39.96, MS$_e$ = 104.15, *p* < 001). Multiple comparisons showed that redundant targets (*M* = 428.3 ms, *SD* = 76 ms) were processed marginally faster than color (*M* = 440 ms, *SD* = 78.2 ms; *t*(7) = 2.77, *p* = .083) and orientation targets (*M* = 472.4 ms, *SD* = 84.5 ms; *t*(7) = 7.51, *p* < .001). Color targets were significantly faster than orientation targets (*t*(7) = 6.37, *p* < .01) . A significant redundancy gain of 13 ms was also observed (*t*(7) = 3.12, *p* < .05). Although no RMI violation was observed (see Figure 6.1, panel e), individual descriptive results showed that five participants presented violations of the RMI on average in 3.8 quantiles (range from 1 to 8).

Practice effect

In order to investigate whether practice could modify results, error percent for each target type is compared through sessions, followed by mean RTs and redundancy gains analysis. Finally, descriptive comparisons of the four RMI results are described.

Error rates. A two-factors repeated measures ANOVA on error percent as a function of Session (1 to 4) and Target Type (no target, color, orientation and redundant targets) was computed. It showed no significant main effect of Sessions (*F*(1.27,8.88) = 2.19, MS$_e$ = 7.76, *p* > .05; Huynh-Feldt-corrected degrees of freedom) and Session x Target Type interaction (*F*(5.73,40.12) = 1.01, MS$_e$ = 3.40, *p* > .05; Huynh-Feldt-corrected degrees of freedom). However, error rates differed significantly for Target Type (*F*(2.68,18.78) = 15.15, MS$_e$ =

7.53, *p* < .001; Huynh-Feldt-corrected degrees of freedom). Multiple comparisons revealed significantly more errors for orientation targets (*M* = 5.1 %, *SD* = 3.2 %) than for redundant (*M* = 1.1 %, *SD* = 1.7 %) and color targets (*M* = 1.5 %, *SD* = 2.1 %; *t*(7) = 5.54, *p* < .01, and *t*(7) = 5.30, *p* < .01, respectively; see Table 6.2). Furthermore, redundant targets generated marginally less errors than color targets (*t*(7) = 2.65, *p* = .099). This advantage of redundantly defined targets which are less likely to be missed is coherent with Krummenacher et al.'s (2002b) findings.

RTs and redundancy gains. RT analysis showed that both main effects were significant (Session: *F*(3,21)= 6.96, MS$_e$ = 2071.56, *p* < .01; target type: *F*(2,14) = 33.88, MS$_e$ = 621.75, *p* < .001). The factor Session additionally showed significant linear (*F*(1,7) = 6.79, MS$_e$ = 4867.12, *p* < .05) and quadratic trends (*F*(1,7) = 15.84, *p* < .01, MS$_e$ = 442.44). However, multiple comparisons revealed that these trends only resulted from the significant RT decrease between Session 1 (*M* = 501.9 ms, *SD* = 49.4 ms) and 2 (*M* = 457.8 ms, *SD* = *t*(7) = 4.78, p < .05; see Table 6.1). For the factor target type, a similar pattern as in the overall analysis was observed, namely a significantly faster detection for redundant (*M* = 445.8 ms, *SD* = 56.7 ms) than for color (*M* = 457.2 ms, *SD* = 60.3 ms) and orientation targets (*M* = 495 ms, *SD* = 63.5 ms; *t*(7) = 3.28, p < .05 and *t*(7) = 6.5, *p* < .01, respectively), and color targets were faster than for orientation targets (*t*(7) = 5.51, p < .01). Moreover, Session and Target Type factors did not interact in a significant way (*F*(6,42) = .62, MS$_e$ = 135.39, *p* > .05). Those observations suggested only a general improvement in the task between Session 1 and 2, RT differences between target dimensions staying equivalent through sessions. The result was confirmed by Miller and Lopes redundancy gains. A one-way repeated measures ANOVA with the factor session revealed that redundancy gains remained similar in each session *F*(3,21) = .65, MS$_e$ = 196.50, *p* > .05).

Table 6.2

Mean error percent (and standard deviation) for each target type and session.

Target dimension	Session 1	Session 2	Session 3	Session 4	Mean
No target	2.34 (1.97)	2.76 (2.72)	3.23 (2.58)	4.17 (3.24)	3.13 (2.39)
Color	1.77 (2.58)	1.25 (1.09)	1.04 (2.30)	2.08 (2.75)	1.54 (2.05)
Orientation	3.96 (2.74)	5.21 (3.50)	4.90 (4.42)	6.15 (4.36)	5.05 (3.18)
Redundant	0.83 (1.26)	1.46 (2.55)	1.15 (1.78)	1.04 (1.46)	1.12 (1.68)
Mean	2.23 (1.70)	2.67 (2.02)	2.58 (2.47)	3.36 (2.68)	

RT distributions (descriptive comparison). RT distributions changed across sessions (see Table 6.3). The number of participants presenting violations of the RMI at one or more quantiles increased from Session 1 (four participants) to Session 3 (all eight participants) before decreasing in Session 4 (five participants). Additionally, the difference between both cumulative curves diminished from Session 1 to Session 2 and two significant RMI test violations were observed in Session 3. Although Session 4 results did not present significant violations anymore, a progress could be observed from Session 1 to 3 (see Figure 6.1, panel b to d), indicating that practice could favor the emergence of evidence of a parallel co-active architecture of feature processing. Note that all participants did not present the same pattern. Three participants showed in each session violations of the RMI, one participant showed only violations in Session 3, one participant in Session 2, two participants in Session 3 and 4, and one participant showed violations of the RMI in the first three sessions. This inter-individual variability suggests that some participants present naturally evidence of a parallel co-active processing, whereas others needed some practice to the same.

Table 6.3

Number of participants presenting individually violations of the RMI and mean number of RMI violations at an individual level.

	Number of participants	Individual RMI violations
Entire experiment	5	2.4
Session 1	4	4.75
Session 2	5	3.2
Session 3	8	3.75
Session 4	5	3.8

6.5. Discussion

The present results suggest that practice does not improve the detection of redundantly defined targets in comparison to singly defined targets (as indicated by the non-significant interaction between Sessions and target type) as observed in Krummenacher et al. (2002b). Although RTs for each target type decreased from Session 1 to Session 2 to level off from Session 2 to Session 4 (similarly to Krummenacher et al., 2002b), the relative difference between each target type remained equivalent. Contrarily to Krummenacher et al.'s (200b) findings, redundancy gains did therefore not increase through sessions but RT distributions were affected by practice. Race Model Inequality analysis provides evidence that the probability to detect a redundantly defined target in comparison to the probability to detect one of the singly defined targets after the same amount of time increases at the fast end of the distribution as a function of the amount of practice. Although not significant, Krummenacher et al. (2002b, Experiment 2) reported violations of the RMI in Session 3. Moreover, inter-individual differences suggested that evidence in favor of a parallel co-active feature processing, when not spontaneously shown (i.e., in the first session), appeared later on. As expected, these findings support the claim that participants need some familiarity with the task for clear evidence of parallel co-active processing to emerge, explaining the lack of RMI violations reported by Poom (2009). The difficulty to report significant violations of the RMI at the first attempt could be attributed to the conservative aspect of the procedure (see Krummenacher et al., 2002b). For this reason, violations of the RMI are easier to observe in experienced participants.

Finally, five participants (about 40% of the sample) were not included because more than ten percent of their trials could not be used. One explanation for this important dropout could be attributed to the lack of feedback throughout the test trials. For instance, Herzog and Fahle (1997) observed that perceptual learning is larger when a feedback is given. Therefore, a feedback would probably help participants to pay more attention to the task.

7. The roles of visual features in the generation of the contextual cueing effect

7.1. Abstract

Previous studies have demonstrated that repeating the context in which a target appears improves performance in a visual search task (Chun & Jiang, 1998). Although this effect, referred to as “contextual cueing”, was initially attributed exclusively to the development of a memory of the object spatial configuration through repetition, recent studies demonstrated that object feature combinations contribute to an efficient cueing of the target location (e.g., Huang, 2006). The present study aims at investigating the relative contribution of different features to the generation of contextual cueing by manipulating one or two object features during the experimental session. Experiment 1 replicates the results of Chun et al.’s seminal study, the following experiments demonstrate that only a change of the color feature is able to abolish contextual cueing (Experiment 2); neither orientation (Experiment 3), nor size (Experiment 7), nor a complete change of all these features (Experiments 4 and 8) did systematically affect contextual cueing. To determine the exact origin of the modulation of contextual cueing observed in Experiment 2, Experiments 5 and 6, respectively, investigated the impact of (color) hue and luminance changes. Results suggest that the finding of Experiment 2 originate from an interaction of both of these color characteristics. Finally, experiments (6, 7 and 8) involving luminance and size changes show that the contextual cueing effect develops faster, demonstrating that object features contribute differently to the contextual cueing.

7.2. Introduction

Orienting oneself in a new environment is difficult. For example, after moving house, making the first cake in the new kitchen takes longer than usual because finding where all the material is takes quite some time. With time and repetitions, no more conscious thinking seems to be needed to complete the task because the “new” context in which objects are located is learned and helps to find them more rapidly.

The facilitatory effect engendered by the learning of a visual context is termed contextual cueing. Chun and Jiang (1998) observed that, in visual search, the detection of a target among heterogeneous distractors was significantly expedited for displays that were repeated throughout the experimental session. In their seminal work participants had to indicate the orientation of the target letter “T” (left or right) among non-target letters “L” all of which were differently orientated (rotated by 0, 90, 180, or 270°; see Figure 7.1) and had different colors (red, green, blue and yellow). Each experimental block was composed of 24 trials. Half of the trials were repeated throughout the whole experiment, whereas the other half was newly generated in each block. In so called “old configuration” trials, at least the spatial configuration of displayed objects was preserved. In the course of the experimental session, performance for old configuration trials became significantly better than the ones obtained for new configuration trials. Chun et al. (1998) suggested that the relationship between the target location and the spatial configuration of the non-targets in the display was progressively learned and guided participants toward the target location. Importantly, participants were unable to distinguish old from new configurations in a recognition task administered at the end of the experiment, leading Chun and Jiang (1998) to conclude that the association was learned implicitly. In a more recent study (Chun & Jiang, 2003) the authors reinforced their argument by demonstrating that indicating the target position was impossible for participants.

Figure 7.1. Schematic example of the search display used in the present study. In old configuration trials each T was associated with the spatial configuration of the Ls. Each L was defined by a particular combination of orientation and, depending on the experiment, color (hue and/or luminance) or size.

Further experiments examined the strength of the contextual cueing effect under different conditions (e.g., Chun & Jiang, 1999; Hodsoll & Humphreys, 2005; Jiang & Song, 2005; Jiang & Wagner, 2004; Peterson & Kramer, 2001). Contextual cueing can reduce the number of eye movements needed to find the target when the configuration is recognized as an old one (Peterson & Kramer, 2001). This effect occurs with displays in pseudo three-dimensional displays (Chua & Chun, 2003), as well as in natural visual scenes (Brockmole, Castelhano, & Henderson, 2006; Brockmole & Henderson, 2006a, b) in which explicit recognition is facilitated because of the larger stimuli richness and variety.

However, not only the spatial configuration, but also distractor features can serve as cues indicating the target position. Chun and Jiang (1999) found that relations between motion trajectories of objects could be learned. In their study, all elements followed their own trajectory across the search display. In this condition, the constant motion of the elements made difficult, if not impossible, to generate an association between the spatial configuration of the distractors and the target. Nevertheless, results demonstrated that participants were able to learn the relation between object trajectories in repeated trials, leading to expedited detection of the target.

The distractor identity can generate a contextual cueing effect as well. By dissociating spatial (object configuration) and object cueing (object identity) that were implicitly combined in Chun and Jiang’s (1998) paradigm, Endo and Takeda (2004) found that, when distractor identities correlated only with the target location, contextual cueing occurred, whereas when the spatial configuration predicted only the target identity, no benefit for repeated trials was observed. The contextual cueing effect thus depends not exclusively on the distractor spatial configuration as initially claimed by Chun and Jiang (1998). Further, Endo and Takeda (2002) found that contextual cueing seem to arise from an additive effect of both spatial and object cueing. According to these results, Endo et al. argued that contextual cueing is more influenced by what is predictive than by what is repeated. Finally, Endo and Takeda (2004) suggested that, when both types of context (spatial configuration and object identity) are predictive of the target location, the most informative type of cueing is learned.

In contrast to the previously cited studies, Huang (2006) designed a series of experiments in which only the combination of spatial configuration and the distractor color arrangement could predict the target location. Results showed that participants were able to learn this conjunctive association. Furthermore, when item colors (hue and luminance) changed in each block (but not the spatial configuration of the color patches), the contextual cueing effect disappeared. Finally, Huang observed more efficient contextual cueing when the color was defined by a chromatic variation (color hue) than by an achromatic (color luminance) variation.

These studies demonstrate that distractors features can cue the target location. What would be the effect of (a) feature change(s) on the development of the contextual cueing effect? Studies investigating the detection of singleton targets demonstrated that a feature change can modulate participants' behavioral response time. Bravo and Nakayama (1992) observed that, when the color of the target and distractors were unpredictable from trial to trial, participants needed more time to complete a discrimination task on the target than when target and distractor colors were kept constant. Similarly, Maljkovic and Nakayama (1994) found a reaction time (RT) cost in a discrimination task for a current trial when the color of the target in the preceding trial differed from the color of the current trial.

By contrast, Treisman (1988) demonstrated that, in a visual search in which distractors features remain constant (e.g., green vertical bars), participants were able to detect a target faster when its defining dimension remained constant (e.g., red or blue targets) than when the target dimension changed from trial to trial (e.g., a red target followed by a left-tilted target). Features (such as red, green, left-, or right-tilted) are considered as variable instances defined on a particular dimension (e.g. color and orientation). Müller and colleagues (Found & Müller, 1996; Müller, Heller & Ziegler, 1995) extended the cross-dimensional cost by analyzing manual RTs of two consecutive trials. Three different types of intertrial transition were compared. In the first type, the target remained identical in two consecutive trials (e.g., a red target followed by a red target), whereas in the second case, the target feature changed (e.g., a red target followed, in the next trial, by a blue target); finally, the target dimension changed across trials (e.g., a red target followed by a left-orientated target). Found et al. (1996) demonstrated that the RT for the current trial increased systematically, but only when the target in the preceding trial was defined in another dimension.

The fact that a feature change can affect participants' behavior suggests that visual search implicates a certain form of learning. Consequently, investigating a feature change permits to evaluate the role of feature arrangements (in the present study, color, orientation and size) in the generation of the contextual cueing effect. Experiment 1 of this study was run to replicate Chun and Jiang's (1998) Experiment 1. In addition, a feature manipulation was introduced in the middle of all the following experiments of the present study. Contrarily to Chun and Jiang's (1998) Experiment 2, in which the whole identity of the distractors changed in the middle of the experiment, the manipulation used in the present study modified one (or two) feature(s) defining items, while the spatial arrangement of the search items in the display remained unchanged. As an example, all elements that were red turned into blue after the middle of the experimental session. Furthermore, in contrast to Huang (2006) who introduced a feature change after each block, a single change allows investigating the relative duration of the manipulation effect. The feature change can either be short-lived and makes the contextual cueing vanish for a brief and limited period of time, or it prevents the development of contextual cueing for a longer period. Experiment 2 evaluated the importance of color, as underlined by Huang (2006). Distractor orientation was changed in Experiment 3 and Experiment 4 tested the impact of a multi-dimensional change of color and orientation. Moreover, the role of two color characteristics, namely hue and luminance, were investigated separately in Experiments 5 and 6. Although Huang (2006) observed a contextual cueing slightly larger when items differed in hue than in luminance, he did not evaluate whether their change affected the contextual cueing effect. Finally, the distractor size was manipulated in Experiments 7 and 8 to investigate whether the contextual cueing behavior is modulated.

7.3. Experiment 1: Replication of Chun and Jiang (1998)

7.3.1. Method

Participants. Seventeen observers (thirteen female and four male) took part in Experiment 1. All were students at the University of Fribourg. They received course credits or were paid at a rate of CHF 5. They were aged between 19 and 41 years (median = 25 years). Sixteen of the observers had normal or corrected to normal vision including color vision. The data of one observer were excluded from analysis due to color blindness. (Investigating the participant's behavior as a control was deemed worthwhile, however.)

Design and procedure. Each trial started with a blank screen of 500ms followed by the presentation for 500 ms, of a fixation cross. Fixation was followed by the presentation of a display containing 12 elements. Eleven of them were Ls and one was a T. The task of the observers was to find the T among Ls and to indicate whether the T was tilted 90 degrees to the left or right. To respond, observers pressed the left arrow key of a standard keyboard when the T was left-tilted and on the right arrow key when it was right-tilted. The display remained visible until a response was triggered.

Experiment 1 consisted of one warm-up block of 24 trials and 30 experimental blocks of 24 trials. In the first experimental block, trials were randomly generated and twelve of them were kept and presented once in each of the following blocks (old configurations). The twelve other trials were newly generated in each block and used as a baseline (new configurations).

Stimuli. Twelve elements (2.52° of visual angle high and wide, with line thickness of 0.4° of visual angle) were displayed in the cells of a virtual matrix of 8 x 6 locations (height: 29.79° of visual angle; width: 21.96° of visual angle). In order to prevent collinearity effects, each element was randomly jittered relative to its central position (maximum horizontal and vertical jitter: 1.15° of visual angle; minimum distance between neighboring elements: 2.86° of visual angle). The target was only presented in the 24 central matrix locations. Half of the targets were allocated to old configurations and the other half to new configurations. Further, an equal number of elements were randomly colored in red (RGB: 255, 0, 0), blue (RGB: 0, 0, 255), green (RGB: 0, 255, 0) and yellow (RGB: 0, 255, 255). In order to replicate Huang's (2006) distinction between color hue and luminance, colors were not made isoluminant. One of the four different orientations (0°, 90°, 180° and 270°) was randomly attributed to the distractor Ls. Positions and orientations of Ls and colors of search elements were randomly re-attributed in each trial of the first block. The color of all elements and the orientation of the Ls were preserved for old configuration trials.

*Apparatus and setting***.** Participants were seated at a distance of approximately 50 cm from a 19" Philips Brilliance P202 monitor controlled by a HP Compaq Business Ultra Slim Desktop Dc7600 personal computer (Pentium IV at 3.2 GHz, 512 Mb RAM). The monitor resolution was set to 1024x768 pixels and its refresh rate to 100 Hz. The experiment was programmed using the Cogent 2000 toolbox (developed by the Cogent 2000 team at the FIL and the ICN and Cogent Graphics developed by John Romaya at the LON at the Wellcome Department of Imaging Neuroscience). The experiment was conducted in a darkened room.

7.3.2. Results and discussion

In order to avoid that extremely slow responses confound the results, RTs slower than 2000 ms were excluded for all the observers (the 2000 ms limit was chosen in function of the overall RT distribution). Next, for each participant, RTs exceeding 2.5 standard deviations of the mean of each configuration and each block were considered outliers and removed from analysis. Further, two "old configuration" displays were excluded because their (randomly generated) spatial allocations allowed an extremely fast detection of the target. Observers indicated an incorrect target orientation in 1.5 % (*SD* = 1.9 %) of old configuration trials and in 2.1 % (*SD* = 2.6 %) of new configuration trials (non-significant difference; *t*(15) = 2.04, *p* = .060). The extremely slow responses excluded from analysis corresponded to 0.1 % (*SD* = 0.3 %) of old configuration trials and 0.5% (*SD* = 0.6 %) of new configurations, while the outliers corresponded to 1.7% (*SD* = 0.8 %) and 1.3% (*SD* = 0.7 %) of old and new configurations, respectively. Finally, all multiple comparisons were adjusted according to the Bonferroni correction where necessary.

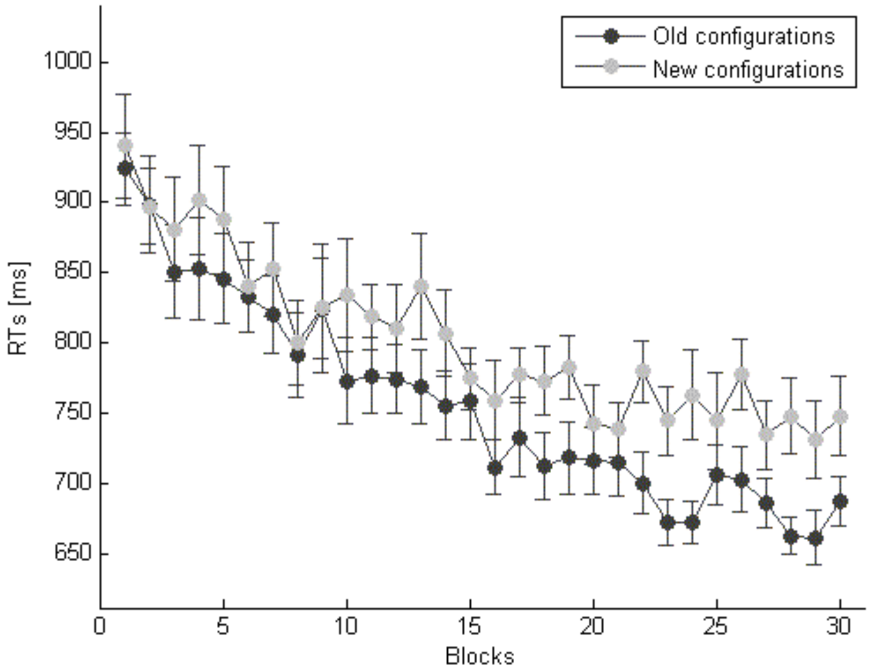

Figure 7.2. Mean RTs (and standard errors) per configuration as a function of the blocks in Experiment 1. The dark grey line represents RTs for old configuration trials, whereas the light grey line stands for the RTs for the new configuration trials.

RTs were first analyzed with a two-way repeated-measures ANOVA with the factors configuration (old, new) an experimental block. The ANOVA revealed a significant main effect of configuration ($F(1,15) = 17.13$, $MS_e = 3059.00$, $p < .001$, Huynh-Feldt-corrected degrees of freedom) and block ($F(11.77, 176.58) = 16.74$, $MS_e = 6412.34$, $p < .001$; Huynh-Feldt-corrected degrees of freedom); the interaction was not significant ($F(23.40, 350.95) = 1.01$, $MS_e = 6349.63$, $p > .10$, Huynh-Feldt-corrected degrees of freedom). [Moreover, linear and quadratic effects on block were observed in both configurations (old: respectively $F(1,15) = 71.14$, $MS_e = 30399.46$, $p < .001$, and $F(1,15) = 17.50$, $MS_e = 7071.91$, $p < .001$; new: respectively $F(1,15) = 55.76$, $MS_e = 21850.65$, $p <.001$, and $F(1,15) = 14.95$, $MS_e = 8621.24$, $p < .01$).]

As suggested by Figure 7.2, targets were detected significantly faster in old configuration trials than in new configuration trials starting with block 10 (block 1: $t(15) = .72$; block 2: $t(15) = .26$; block 3: $t(15) = .80$; block 4: $t(15) = 1.76$; block 5: $t(15) = 1.19$; block 6: $t(15) = .60$; block 7: $t(15) = .87$; block 8: $t(15) = .12$; block 9: $t(15) = -.11$, all $p > .10$).

Table 7.1

Mean RTs (ms) for new and old configurations per epoch in Experiment 1, with each epoch comprising 5 blocks (standard deviations in parentheses), F values of the simple contrast between old and new configurations.

	Epoch 1	**Epoch 2**	**Epoch 3**	**Epoch 4**	**Epoch 5**	**Epoch 6**
New configuration	905.97	831.94	811.38	773.35	760.46	752.42
	(127.13)	*(121.17)*	*(106.95)*	*(84.91)*	*(75.46)*	*(91.75)*
Old configuration	875.18	811.84	769.73	722.18	691.75	684.52
	(117.69)	*(116.24)*	*(88.21)*	*(78.62)*	*(64.77)*	*(56.97)*
F(1,15)	2.40	2.44	9.70	16.43	43.05	16.71
p	.142	.139	.007	.001	.000	.001

As in Chun and Jiang (1998), to increase statistical power, blocks were regrouped into six epochs. RT means per epoch for each configuration type (see Table 7.1) were analyzed with a two-way repeated-measures ANOVA with the factors configuration (old, new) and epoch. Results show significant effects of configuration ($F(1,15) = 12.81$, $MS_e = 6747.52$, $p < .01$, Huynh-Feldt-corrected degrees of freedom) and epoch (*F*(2.46,36.84) = 41.83, MS$_e$ = 6784.04, *p* < .001, Huynh-Feldt corrected degrees of freedom), as well as a significant interaction (*F*(5,75) = 3.73, MS$_e$ = 832.29, *p* < .01). [Further, the factor epoch showed significant linear (*F*(1,15) = 74.56, MS$_e$ = 8691.62, *p* < .001) and quadratic effects (*F*(1,15) = 17.36, MS$_e$ = 2596.18, *p* < .001).] The same analysis on error rates did not revealed any significant main effects (configuration: *F*(1,15) = 1.27, MS$_e$ = 3.93, *p* > .10, Huynh-Feldt corrected degrees of freedom; epoch: *F*(2.26,33.85) = 2.04, MS$_e$ = 9.42, *p* > .10, Huynh-Feldt corrected degrees of freedom; the interaction was not significant, either: *F*(5,75) = .69, MS$_e$ = 3.92, *p* > .10).

Experiment 1 replicated Chun and Jiang's (1998) results of their initial experiment, namely that there are RT benefits for old relative to new configurations that increase as a function of epoch (see Figure 7.3). However, there were two main differences between Chun et al.'s and the present results. First, detection times in the present experiment were around 200 ms faster than in the original paper. Second, the difference between old and new configurations in the current experiment increased constantly, whereas in the original report the contextual cueing effect seemed to reach a maximum already in epoch 2. However, discrepancies such as these were observed in Chun and Jiang (1998)'s following experiments.

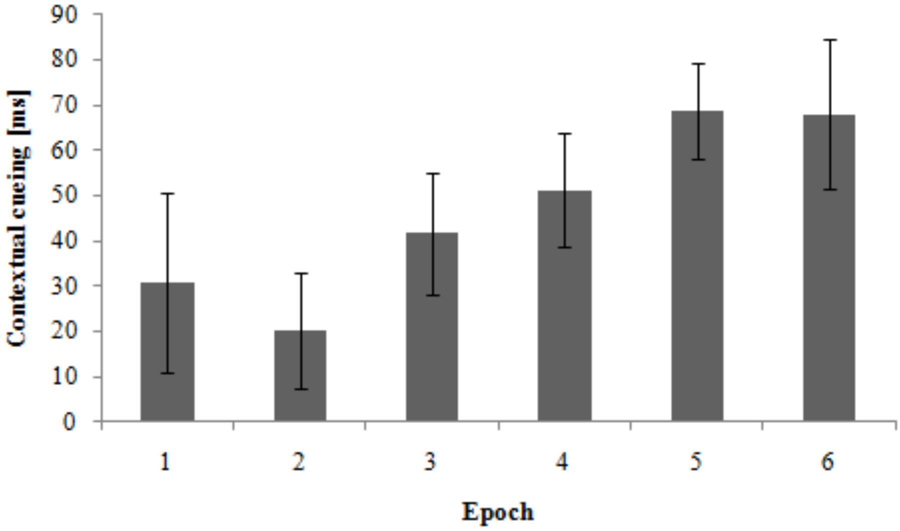

Figure 7.3. Contextual cueing effect (and standard error) as a function of epochs in Experiment 1. The contextual cueing effect represents the difference between target detection time in old and new configurations. A positive value indicates a benefit of the old configuration.

In order to compare the results of present Experiment 1 with the following experiments employing a slightly reduced number of blocks (following Huang, 2006), mean RTs were recomputed from the 24 first blocks and four blocks were averaged per epoch (see Table 7.2 and Figure 7.4). The results were similar to those obtained with the entire data set and showed significant main effects of configuration ($F(1,15) = 12.81$, $MS_e = 6747.52$, $p < .01$, Huynh-Feldt-corrected degrees of freedom) and epoch ($F(5,15) = 30.79$, $MS_e = 4044.23$, $p < .001$), as well as a significant interaction ($F(5,75) = 2.98$, $MS_e = 982.83$, $p < .05$). [Significant linear ($F(1,15) = 60.20$, $MS = 605391.50$, $p < .001$) and quadratic effects ($F(1,15) = 6.59$, $MS_e = 12894.36$, $p < .05$) were also observed for the factor epoch.] As in the initial analysis, error rates were affected neither by configuration ($F(1,15) = .39$, $MS_e = 1.82$, $p > .10$, Huynh-Feldt-corrected degrees of freedom), nor epoch ($F(2.91,55.22) = 1.09$, $MS_e = 2.14$, $p > .10$, Huynh-Feldt-corrected degrees of freedom). The factors did not interact, either: $F(4.69,70.28) = .62$, $MS_e = 3.46$, $p > .10$, Huynh-Feldt-corrected degrees of freedom).

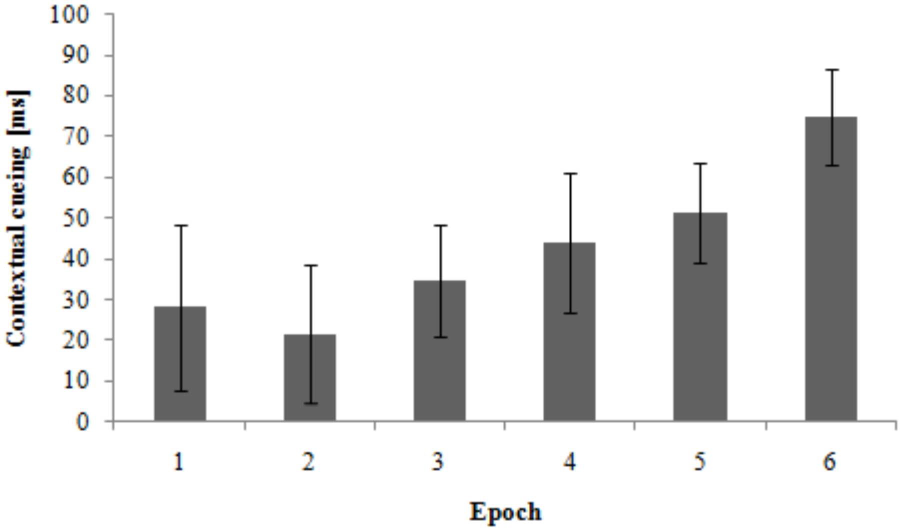

Figure 7.4. Contextual cueing effect (and standard error) in Experiment 1 for epochs regrouping four blocks.

Further, to provide a standard for comparison with following experiments in which a feature manipulation was introduced in the middle of the testing session, supplementary analyses were run. First, RTs for the first and the second half of the session were computed for each configuration type and compared with a two-way repeated-measures ANOVA with the factors manipulation (before, after) and configuration (old, new). The ANOVA revealed (replicating previous results) a significant main effect of manipulation ($F(1,15) = 52.19$, $MS_e = 2878.52$, p

< .001, Huynh-Feldt-corrected degrees of freedom) and configuration (*F*(1,15) = 12.81, MS_e = 2249.17, *p* < .01, Huynh-Feldt-corrected degrees of freedom), as well as a significant interaction (*F*(1,15) = 6.65, MS_e = 489.17, *p* < .05, Huynh-Feldt-corrected degrees of freedom). Multiple comparisons demonstrated that targets were detected significantly faster in old configuration trials (*M* = 832.3 ms, *SD* = 110.4 ms) than in new configuration trials (*M* = 860.5 ms, *SD* = 114.1 ms) in the second half of the experiment (*F*(1,15) = 27.85, *p* < .001), but not in the first half (old configuration: *M* = 721.1 ms, *SD* = 70.5 ms; new configuration: *M* = 777.8 ms, *SD* = 81.9 ms; *F*(1,15) = 3.50, *p* = .081).

Table 7.2

Mean RTs (ms) for new and old configurations per epoch in Experiment 1, with each epoch comprising 4 blocks (standard deviations in parentheses), F values of the simple contrast between old and new configurations.

	Epoch 1	**Epoch 2**	**Epoch 3**	**Epoch 4**	**Epoch 5**	**Epoch 6**
New configuration	909.90	846.47	825.01	797.12	774.80	761.54
	(126.21)	*(122.36)*	*(116.47)*	*(106.28)*	*(85.02)*	*(69.82)*
Old configuration	881.86	824.81	790.20	753.13	723.66	686.59
	(115.95)	*(106.50)*	*(120.80)*	*(79.93)*	*(88.33)*	*(65.13)*
F(1,15)	1.93	1.64	6.51	6.67	17.59	40.46
p	.185	.220	.022	.021	.001	.000

7.4. Experiment 2: Color change

Experiment 2 investigated the effect of a color change in the middle of the experiment on the contextual cueing generation. In contrast to Huang's (2006) manipulation in which different colors were used in each block, the color change used in the present experiment was less striking. The displayed colors remained identical throughout the experiment, but were attributed to other elements after the middle of the experimental session. With this subtle change, it was possible to gauge the strength of the association between distractor colors and target location. If the feature color plays an important role in the development of contextual cueing, even such a faint change should disturb the effect.

7.4.1. Method

Participants. Sixteen observers (fourteen female and two male) took part in Experiment 2. All were students at the University of Fribourg. They received course credits or were paid at a rate of CHF 5. They were aged between 19 and 41 years (median = 24 years). All observers had normal or a corrected to normal vision, including normal color vision.

Design, procedure and stimuli. The general design of Experiment 2 differed from the design of Experiment 1 (replication) in two respects. First, Experiment 2 contained 24 blocks (instead of 30 in Experiment 1). Participants had shown contextual cueing in shorter experiments (e.g. Brockmole, Castelhano & Henderson, 2006; Chun & Jiang, 1999; Endo & Takeda, 2002), therefore and to reduce the strain put on participants it was decided to run the slightly shorter version. Second, and more importantly, the color of all display elements changed in the middle of the experiment (from block 13): elements that were red in the first half of experiment (blocks 1-12) turned into green (green into blue, blue into yellow and yellow into red) in the second half of the experiment (blocks 13-24).

*Apparatus and setting***.** Apparatus and setting were the same as in Experiment 1.

7.4.2. Results and discussion

The same analysis procedure as in Experiment 1 was used. (No old configuration trials needed to be excluded because they facilitated target detection as two of the old configurations of Experiment 1 did.) Observers made, on average, errors in 1.8 % (*SD* = 1.4 %) of trials in old configuration trials and in 1.9 % (*SD* = 1.6 %) of new configuration trials (non-significant difference: $t(15) = .49$, $p > .10$). Extremely slow responses corresponded to 0.4 % (*SD* = 0.7 %) of old configuration trials and 0.9 % (*SD* = 1.1 %) of new configurations trials; outliers corresponded to 2.0 % (*SD* = .7 %) and 2.4 % (*SD* = 1.0 %) of old and new configurations, respectively.

Figure 7.5 depicts the RTs obtained in Experiment 2.The configurations (old, new) x block repeated-measures ANOVA showed a significant effect of the block ($F(16.00,240.04) = 9.1$, $MS_e = 15709.11$, $p < .05$) [reflecting significant linear ($F(1,15) = 65.79$, $MS_e = 32381.59$, $p < .001$) and quadratic effects ($F(1,15) = 5.05$, $MS_e = 13503.21$, $p < .05$)]. No differences were to observed between configurations ($F(1,15) = 1.84$, $MS_e = 45326.07$, $p > .10$). The factors did not interact, either ($F(19.32, 289.78) = 1.00$, $MS_e = 8054.06$, $p > .10$). As in Experiment 1, RT means (see Table 7.3) were regrouped into epochs.

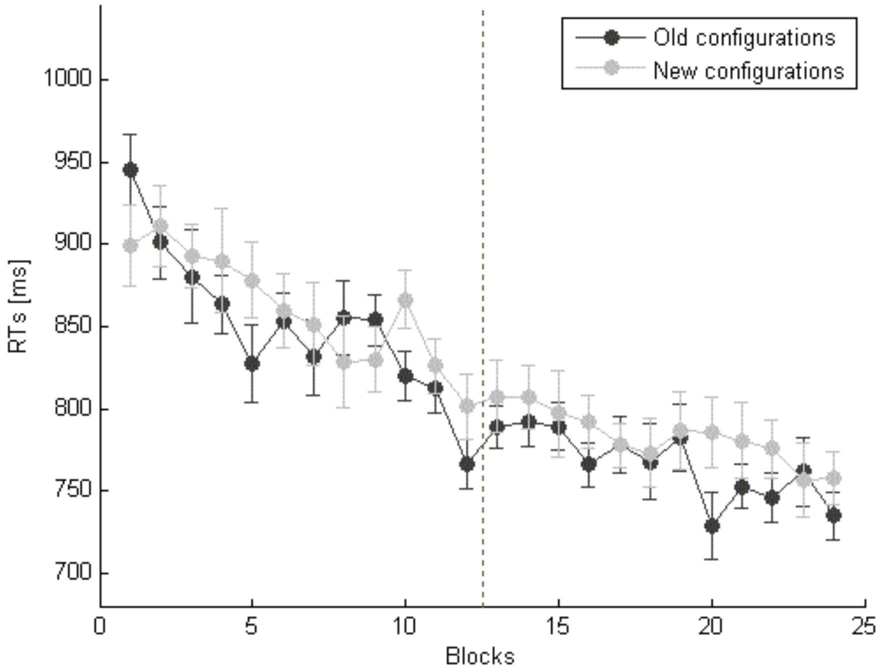

Figure 7.5. Mean RTs (and standard errors) per configuration and block in Experiment 2. The dark grey line represents RTs for old configuration trials, whereas the light grey line stands for the RTs for the new configuration trials. The dashed line represents the manipulation location.

A two-way (configuration: old, new; epoch) repeated-measures ANOVA showed a significant effect of epoch ($F(5,15) = 21.26$, $MS_e = 4078.38$, $p < .001$). Neither the main effect of configuration nor the interaction between configuration and epoch were statistically significant (main effect of configuration: $F(1,15) = .91$, $MS_e = 10148.38$, $p > .10$, Huynh-Feldt-corrected degrees of freedom; interaction: $F(5,75) = .233$, $MS_e = 1576.33$, $p > .10$). [The factor epoch showed a significant linear effect ($F(1,15) = 59.86$, $MS_e = 416467.80$, $p < .001$) and a marginally significant quadratic effect ($F(1,15) = 4.43$, $MS_e = 15496.77$, $p = .053$) as in Chung and Jiang (1998)'s experiments.] Error analyses showed neither of the main effects nor the interaction to be significant (main effect of configuration: $F(1,15) = .24$, $MS_e = .80$, $p < .10$, Huynh-Feldt-corrected degrees of freedom; main effect of epoch: $F(5,75) = .87$, $MS_e = .47$, $p < .10$; interaction: $F(5,75) = .58$, $MS_e = 1.11$, $p < .10$).

Table 7.3

Mean RTs (ms) for new and old configurations per epoch in Experiment 2 (standard deviations in parentheses), F values of the simple contrast between old and new configurations.

	Epoch 1	**Epoch 2**	**Epoch 3**	**Epoch 4**	**Epoch 5**	**Epoch 6**
New configuration	898.22	854.36	830.96	800.94	780.74	767.55
	(115.75)	(133.36)	(95.73)	(83.80)	(108.81)	(86.52)
Old configuration	897.45	841.83	813.04	783.94	764.34	748.82
	(126.39)	*(123.83)*	*(95.61)*	*(89.64)*	*(97.66)*	*(104.66)*
F(1,15)	0.00	0.30	0.91	1.83	0.92	0.74
p	.972	.589	.355	.196	.352	.404

*Analyses of effects of the color manipulation***.** Because the color change manipulation could have had either temporally local (limited to a certain period of time) or a global (unlimited period of time) influence on performance of the second half of the experimental session, RT data were analyzed at different scales. The first step evaluates the impact of the color manipulation on the contextual cueing effect on performance in Experiment 2 (within-experiment), while the subsequent step analyzes the effect of the manipulation by comparing results of Experiment 2 to the results of Experiment 1 (between-experiment). Each of both within- and between-experiment sections investigated first a feature (here, color) manipulation effect at a global level by comparing (old and new) configurations in two halves of an experiment, followed by the examination of the manipulation effect at a local level by comparing epochs 3 and 4 (The procedure developed here is also used in all following experiments).

Within-experiment analyses. The change of the object color in the middle of the experiment seemed to have made the contextual cueing disappear. Indeed, despite a task learning effect (overall decrease in RTs), reflected by significant linear and quadratic effects reflected by the factor epoch, no difference between old and new configurations, and no interaction between epoch and configuration, were observed. In order to test the effect of the color manipulation, RTs before and after the middle of the testing session were analyzed for the two configuration types. A two-way repeated-measures ANOVA with the factors manipulation (before, after) and configuration (old, new) revealed a significant main effect of manipulation ($F(1,15)$ =

50.72, $MS_e = 2100.14$, $p < .001$, Huynh-Feldt-corrected degrees of freedom). RTs after the manipulation (*M* = 856.0 ms, *SD* = 25.3 ms) were significantly faster than before the manipulation (*M* = 774.4 ms, *SD* = 21.0 ms). The main effect of configuration was not statistically significant: $F(1,15) = .91$, $MS_e = 3382.78$, $p > .10$, Huynh-Feldt-corrected degrees of freedom; neither was the interaction: $F(1,15) = .36$, $MS_e = 544.13$, $p > .10$, Huynh-Feldt-corrected degrees of freedom). Similar results were observed in the analysis of epochs 3 and 4, marking the transitions of color assignments: the main effect of manipulation was significant: $F(1,15) = 8.68$, $MS_e = 1611.08$, $p < .05$; the main effects of configuration $F(1,15) = 1.66$, $MS_e = 3339.18$, $p > .05$; and the interaction $F(1,15) = .01$, $MS_e = 745.37$, $p > .10$, all corrected with Huynh-Feldt degrees of freedom) were not. In addition, the color change did not affect error rates, neither at the experiment, nor at the epoch level (experiment: manipulation: $F(1,15) = .24$, $MS_e = .74$, $p > .10$; configuration: $F(1,15) = .05$, $MS_e = .38$, $p > .10$; interaction: $F(1,15) = .67$, $MS_e = 1.41$, $p > .10$; epoch: $F(1,15) = .22$, $MS_e = .64$, $p > .10$; configuration: $F(1,15) = .04$, $MS_e = .45$, $p > .10$; interaction: $F(1,15) = .84$, $MS_e = 1.45$, $p > .10$, all corrected with Huynh-Feldt degrees of freedom).

Between-experiments analyses. Although previous analyses already indicated that the color change in the middle of the experiment abolishes the development of the contextual cueing effect, the contextual cueing effect of the present Experiment 2 was compared to the effect of Experiment 1 (see Figure 7.6). The two first analyses investigated the manipulation effect on a global level (i.e., by comparing the magnitude of the contextual cueing in the first and second part of the experiment and the contextual index slopes after the manipulation between both experiments), while the last one evaluated the immediate effect of the manipulation (i.e., by comparing the contextual cueing slope between epoch 3 and 4 in both experiments).

First, the contextual cueing effect was computed across the first and the second half of each Experiments 1 and 2. A two-way mixed-measures ANOVA with the factors manipulation (before, after) and experiment (Experiment 1, Experiment 2) showed that, although the main effect of the experiment ($F(1,30) = 2.31$, $MS_e = 5631.96$, $p > .10$) and the interaction between experiment and manipulation ($F(1,30) = 1.80$, $MS_e = 1033.30$, $p > .10$, Huynh-Feldt-corrected degrees of freedom) did not reached statistical significance, the contextual cueing effect before the manipulation (*M* = 19.3 ms, *SD* = 63.4) was significantly smaller than after the manipulation (*M* = 37.0 ms, *SD* = 54.0 ms; $F(1,30) = 4.88$, $MS_e = 1033.30$, $p > .10$, Huynh-Feldt-corrected degrees of freedom). Multiple comparisons revealed that the benefit for old configurations was similar in the first half of each experiment (Experiment 1, *M* = 28.2 ms, *SD* = 60.3 ms; Experiment 2, *M* = 10.4 ms, *SD* = 67.1 ms; *F*(1,30) = .62, *p* > .10); however, in the second half of the experiments, the benefit was significantly smaller in Experiment 2 (*M* = 17.4 ms, *SD* = 57.9 ms) than in Experiment 1 (*M* = 56.7 ms, *SD* = 43.0 ms; *F*(1,30) = 4.76, *p* < .05).

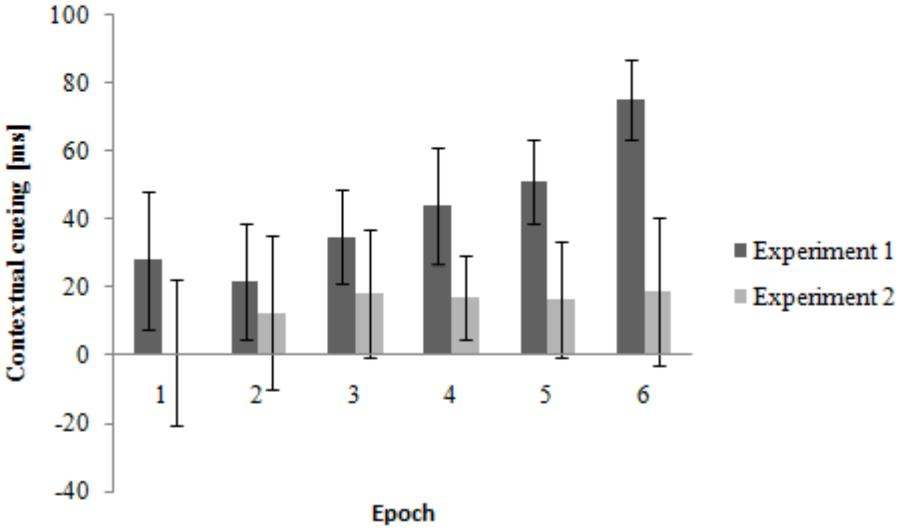

Figure 7.6. Comparison of the contextual cueing effect between Experiment 1 and 2. Error bars represent standard errors. Note that epochs 3 and 4 mark the transition trials before and after the color manipulation in Experiment 2.

The second analysis examined whether the feature change would interfere with the gradual increase of the contextual cueing effect on search performance as observed in Experiment 1. To evaluate the development of contextual cueing in both Experiments 1 and 2, the RT slopes computed from the contextual cueing effects of epochs 4 to 6, in Experiment 1 and 2, respectively, were compared. Slopes were respectively 15.5 ms (Experiment 1) and .9 ms (Experiment 2). Although the difference between slopes was not statistically significant (*t*(30) = 1.32, *p* < .10), the slope in Experiment 1was clearly positive (*M* = 15.5 ms, *SD* = 30.3 ms) whereas the slope in Experiment 2 close to 0 (*M* = .9 ms, *SD* =32.1 ms). This result provides further evidence for the assumption that changing the color of elements prevents the development or the generation of the contextual cueing effect.

A last analysis compared the slope between epochs 3 and 4 for both Experiments 1 and 2 in order to determine if the feature manipulation affected search performance on a local level. As in the slope comparison reported above, the slope between epochs 3 and 4 of Experiment 2 was slightly negative (*M* = -.9 ms, *SD* = 54.6 ms) and the slope for Experiment 1 was positive

(*M* = 9.2 ms, *SD* = 59.3 ms), but the difference between slopes did not reach statistical significance ($t(30) = .50, p > .10$).

To sum up, results of Experiment 2 indicate that changing the color of all elements in the middle of the experimental session disturbs the generation or development of contextual cueing. Comparing the benefit for old configurations between Experiments 1 and 2 revealed that the experimental manipulation durably hinders the (gradual) development of the contextual cueing effect. These results are coherent with the findings by Huang (2006), demonstrating that a color change in old configurations (while maintaining the spatial configuration of the color patches) in each block suppresses the contextual cueing effect over an extended period of time. The disappearance of contextual cueing following a color change suggests therefore that color efficiently cues the target location. At the same time this observation confirms the assumption that the contextual cueing effect stems from the interaction of both object (feature) and spatial cues (Endo & Takeda, 2002, 2004). If cueing were solely due to the spatial configuration of objects in the display, a color change would not have disturbed its development.

7.5. Experiment 3: Orientation change

Experiment 3 investigated the effect of a change in the second feature defining the distractors, namely orientation. It can be assumed that, as a color change, changing the orientation feature in the middle of the experimental session prevents the development of contextual cueing. Moreover, the orientation feature potentially is of higher importance for the present search task than color. The degree of heterogeneity in the orientation of the L distractors is highly likely to be the very cause for the difficulty of the search task. If it were surrounded by homogeneous upwards-oriented Ls, the target T would pop out of the display, which is not the case any longer when Ls have various orientations (e.g., Wolfe & Horowitz, 2004). On the other hand, if all elements share the same color, but not the same orientation, the task difficulty would not disappear. Task difficulty depends on the variable distractor orientation, but the orientation feature does not provide (additional) information useful for the identification of the target location in old configuration trials as color seems to do. From this perspective, an orientation change should not affect contextual cueing.

7.5.1. Method

Participants. Sixteen observers (fourteen female and two male) took part in Experiment 3. All were students at the University of Fribourg. They received course credits or were paid at a rate of CHF 5. They were aged between 19 and 32 years (median = 20 years). All observers had normal or corrected to normal vision, including normal color vision.

Design, procedure and stimuli. The design of Experiment 3 was similar to that of Experiment 2, with the exception that in Experiment 3 the orientation of all distractors changed in the middle of the experiment (at the beginning of block 13). In detail, Ls that were 0°-tilted in the first half of Experiment 3 were changed into 180°-tilted Ls for the remainder of the second half the experiment. Analogously, 90°-tilted Ls were changed into 270°-tilted, 180°-tilted Ls to 0°, and 270°-tilted Ls to 90°-tilted Ls.

Apparatus and setting. Apparatus and setting were the same as in Experiments 1 and 2.

7.5.2. Results and discussion

Error rates were, on average, at 2.2 % (*SD* = 1.62 %) in old configuration trials and 1.8 % (*SD* = 1.4 %) in new configuration trials (marginally significantly different: $t(15) = 2.1$, $p = .053$). Extremely slow responses corresponded to 0.8 % (*SD* = 1.1 %) of old configuration trials and 1.5% (*SD* = 1.1%) of new configuration trials, and outliers corresponded to 2.2 % (*SD* = 0.9 %) and 2.1 % (*SD* = 0.7 %) of old and new configuration trials, respectively.

Figure 7.7 depicts results of Experiment 3. The configurations (old, new) x block repeated-measures ANOVA of RTs revealed a significant effect of the factor block ($F(3.74,56.10) = 27.12$, $MS_e = 5040.90$, $p < .001$, Huynh-Feldt-corrected degrees of freedom), [accompanied by significant linear ($F(1,15) = 56.90$, $MS_e = 34497$, $p < .001$) and quadratic effects ($F(1,15) = 13.71$, $MS_e = 6689.87$, $p < .01$)]. The main effect of configuration was marginally significant ($F(1,15) = 3.15$, $MS_e = 50702.88$, $p = .096$, Huynh-Feldt-corrected degrees of freedom), whereas the interaction between factors did not reach statistical significance ($F(23,345) = 1.26$, $MS_e = 6680.46$, $p > .10$).

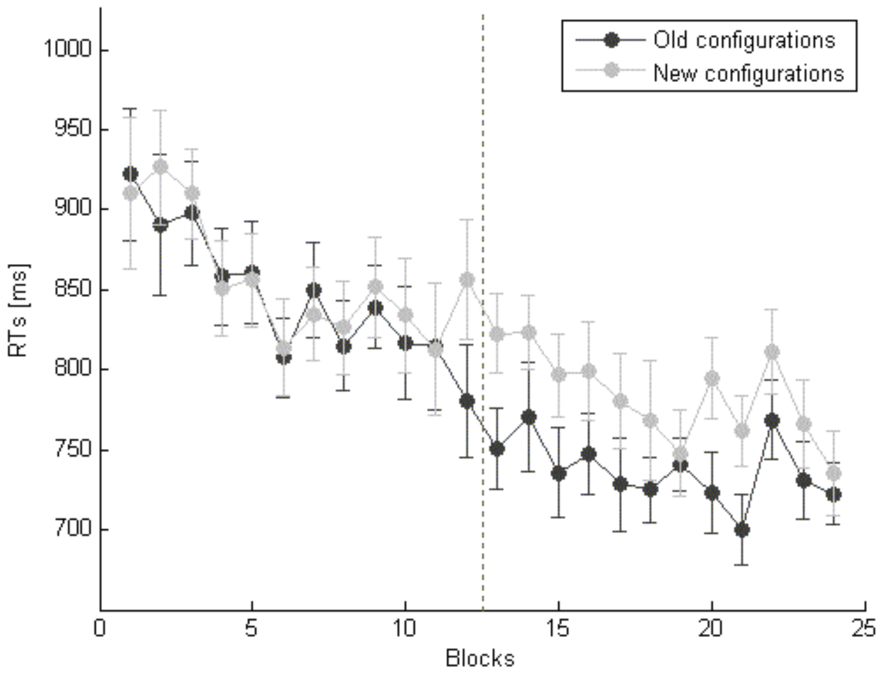

Figure 7.7. Mean RTs (and standard errors) per configuration and block in Experiment 3. The dark grey line represents RTs for old configuration trials, whereas the light grey line stands for the RTs for the new configuration trials. The dashed line represents the manipulation location.

After regrouping blocks into six epochs (see Table 7.4), a two-way repeated-measures ANOVA with the factors configuration (old, new) and epoch showed a significant main effect of epoch ($F(3.74,56.10) = 27.12$, $MS_e = 5040.90$, $p < .001$, Huynh-Feldt-corrected degrees of freedom) and a tendency of a significant main effect of configuration ($F(1,15) = 3.15$, $MS_e = 12675.71$, $p = .096$, Huynh-Feldt-corrected degrees of freedom), as well as a significant interaction ($F(5,75) = 2.89$, $MS_e = 1420.67$, $p < .01$). The factor epoch showed significant linear ($F(1,15) = 54.99$, $MS_e = 8654.87$, $p < .001$) and quadratic effects ($F(1,15) = 11.89$, $MS_e = 1501.61$, $p < .01$). Error analyses showed no significant main effects (configuration: $F(1,15) = 4.41$, $MS_e = .47$, $p = .053$, Huynh-Feldt corrected degrees of freedom; epoch: $F(5,75) = 2.18$, $MS_e = .85$, $p = .065$), the interaction: $F(5,75) = 1.11$, $MS_e = .82$, $p < .10$) was not significant, either.

The results of Experiment 3 are comparable to those obtained in Experiment 1. The orientation change in the middle of the experiment seems not to have disturbed the generation and development of contextual cueing. The effect of the manipulation effect was, however, examined in detail (as in Experiment 2).

Table 7.4

Mean RTs (ms) for new and old configurations per epoch in Experiment 3 (standard deviations in parentheses), F values of the simple contrast between old and new configurations.

	Epoch 1	**Epoch 2**	**Epoch 3**	**Epoch 4**	**Epoch 5**	**Epoch 6**
New configuration	899.48	832.90	838.90	810.68	772.99	769.03
	(118.38)	(98.48)	(121.25)	(82.53)	(101.82)	(79.77)
Old configuration	892.37	833.52	812.99	751.53	729.73	730.82
	(128.49)	(103.44)	(123.78)	(98.07)	(73.92)	(72.10)
F(1,15)	.085	.001	2.402	6.614	4.708	3.910
p	.775	.972	.142	.021	.046	.067

Within-experiment analyses of the orientation manipulation. A two-factors (configuration x manipulation) repeated-measures ANOVA of the RTs of Experiment 3 revealed that, although no significant main effect of configuration was observed ($F(1,15) = 3.15$, $MS_e = 4225.24$, $p > .10$), a main effect of the manipulation ($F(1,15) = 58.98$, $MS_e = 2241.36$, $p < .001$) as well as an interaction were found ($F(1,15) = 7.50$, $MS_e = 694, 29$, $p < .05$). Multiple comparisons unveiled that, although old ($M = 846.4$ ms, $SD = 27.8$ ms) and new configurations ($M = 857.1$ ms, $SD = 26.3$ ms) were statistically not different from RTs before the manipulation ($F(1,15) = .42$, $p > .10$), RTs were significantly faster for old configurations ($M = 737.4$ ms, $SD = 18.7$ ms) than for new configurations ($M = 784.2$ ms, $SD = 20.7$ ms) after the manipulation ($F(1,15) = 6.50$, $p < .05$). Although these findings suggested that the contextual cueing benefit was increased by the color manipulation, it is important to note that, as depicted in Figure 7.6, a significant advantage for the old configurations was observed just before the manipulation, in block 12 (multiple comparison: $F(1,15) = 8.38$, $p < .05$).

However, the orientation change had an impact on error rates. Although no significant interaction between the factors configuration and manipulation was revealed ($F(1,15) = .84$, $MS_e = .83$, $p < .10$, Huynh-Feldt-corrected degrees of freedom), the error rate after the manipulation (*M* = 1.94 %, *SD* = 1.52 %) was significantly higher than before the manipulation (*M* = 1.25 %, *SD* = 0.89 %; *F*(1,15) = 7.72, MS_e = 1.00, *p* > .05, Huynh-Feldt-corrected degrees of freedom), while the error rate for old configurations (*M* = 1.77 %, *SD* = 1.30 %) was slightly larger than for new configuration (*M* = 1.42 %, *SD* = 1.07 %; *F*(1,15) = 4.41, MS_e = .44, *p* = .053, Huynh-Feldt-corrected degrees of freedom). Further, multiple comparisons revealed a tendency for error rates in old configurations to increase after the manipulation (before manipulation: *M* = 1.32 %, *SD* = 0.95%, after manipulation: *M* = 2.22 %, *SD* = 2.01 %; *F*(1,15) = 4.12, *p* = .059), and the error rate in new configurations was significantly larger after the manipulation (before manipulation: *M* = 1.18, *SD* = 1.07, after manipulation: *M* = 1.67, *SD* = 1.18; *F*(1,15) = 7.14, *p* < .05).

Comparing RTs of epochs 3 and 4 between both configuration types showed, despite small differences, comparable results to the previous analysis of RTs at a global level (main effect of manipulation: *F*(1,15) = 6.76, MS_e = 4739.76, *p* < .05; main effect of configuration: *F*(1,15) = 5.50, MS_e = 5264.90, *p* < .05; interaction: *F*(1,15)= 3.68, MS_e = 1203.02, *p* = .074, all Huynh-Feldt-corrected degrees of freedom); the differences between configurations was significant only after the manipulation, as already shown in Table 7.4 (before manipulation: *F*(1,15) = 2.40, *p* > .05; after manipulation: *F*(1,15) = 6.61, *p* < .10). Error rates, on the level of the within-experiment analysis, were not affected by the manipulation of the orientation (main effect of configuration: *F*(1,15) = 2.72, MS_e = .47, *p* > .10; main effect of manipulation: *F*(1,15) = 1.73, MS_e = .73, *p* > .10; interaction: *F*(1,15) = 1.58, Ms_e = .80, *p* < .10). The findings suggested that the differences in error rates observed at the global level was not due to a sudden increase after the manipulation, rather it persisted over an extended period of time.

Between-experiments analyses of the orientation manipulation. The first global level analysis was not able to differentiate between Experiment 3 and Experiment 1. The two-way mixed-measures ANOVA comparing the mean magnitude of contextual cueing before and after the orientation manipulation across both experiments revealed no significant main effect of the factor experiment (*F*(1,30) = .46, MS_e = 6474.41, *p* > .10), the interaction between manipulation and experiment was not significant, either (*F*(1,30) = .19, MS_e = 1183.46, *p* > .10, Huynh-Feldt corrected degrees of freedom). The finding that the magnitude of contextual value was significantly higher after (*M* = 51.8 ms, *SD* = 59.5 ms) than before the manipulation (*M* = 19.5 ms, *SD* = 63.1 ms; *F*(1,30) = 14.11, MS_e = 1183.46, *p* < .001; Huynh-Feldt corrected degrees of freedom) agrees with the predicted augmentation of the contextual cueing effect as a function of the number of repetitions of old displays. Multiple comparisons confirmed the assumption that contextual cueing is significantly larger in the second half of the experiment in Experiment 1 (first half of the experiment: *M* = 28.2 ms, *SD* = 60.3 ms, second half of the experiment: *M* = 56.7 ms, *SD* = 43.0 ms; *F*(1.30) = 5.50, *p* < .05) than in Experiment 3 (first half of the experiment: *M*= 10.8 ms, *SD* = 66.5 ms, second half of the experiment: *M* = 46.9 ms, *SD* = 73.6 ms; *F*(1,30) = 8.78, *p* > .01).

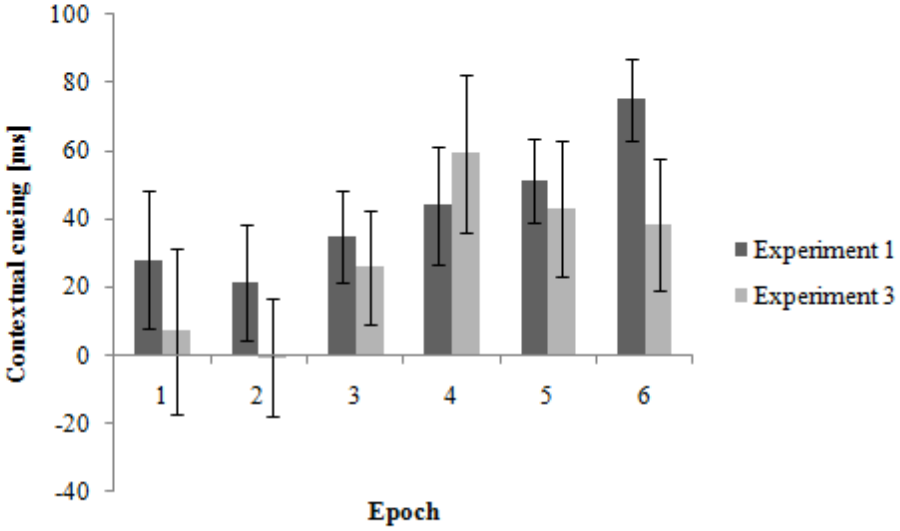

Figure 7.8. Comparison of the contextual cueing effect between Experiment 1 and 3. Error bars represent standard errors.

However, as shown in Figure 7.8, contrary to Experiment 1, the magnitude of contextual cueing is reduced after the orientation manipulation. The observation was confirmed by the slope analysis (*t*(30) = 2.26, *p* < .05), demonstrating that the slopes diverged significantly. While contextual cueing continued to increase in Experiment 1 (*M* = 15.5 ms, *SD* = 30.3 ms), it decreased in Experiment 3 (*M* = -10.5 ms, *SD* = 34.5 ms). Finally, at a local level, although the slope between epochs 3 and 4 was steeper in Experiment 3 (*M* = 33.25, *SD* = 69.37) than in Experiment 1 (*M* = 9.18, *SD* = 59.34), slopes were statistically no different (*t(*30) = -1.06, *p* > .10). That fact that the reduction in the amount of contextual cueing did not appear directly after the manipulation indicates that the orientation changes did not have an effect on a short time range. A more suitable explanation can be found in the RTs. In old configuration trials, RTs stabilized at epochs 5 and 6, whereas, in new configuration trials, RTs continued to decrease, what caused a reduction of the magnitude in the contextual cueing effect. This suggests that the learning effect in old configuration trials allows participants to reach a minimum detection time threshold faster than in new configuration trials.

To sum up, despite a negative slope after the manipulation, the other analyses of Experiment 3 provide evidence for the interpretation that changing the orientation of all distractors did not affect the contextual cueing effect. However, participants made generally more errors after the manipulation, leading to the assumption that this latter does not disturb the development of the contextual cueing, if contextual cueing is assumed to take place on an early perceptual level of processing; rather the response selection process seems to be affected. This result seems consistent with the assumption that orientation, because of its direct implication in search difficulty, cannot efficiently cue the target location. In addition to the spatial configuration of the distractors, participants can use their color as cues expediting target detection.

7.6. Experiment 4: Color and orientation change

The results of Experiments 2 to 3, as compared to the findings of Experiment 1, suggest that a change of the colors of distractor items can stop the generation and development of contextual cueing, whereas an orientation change seems to increase the error rate but not RTs. How does a change of both features change in the middle of the experiment affect performance? According to Experiment 2, a color change would stop the development of contextual cueing and, according to Experiment 3, an orientation change would not affect contextual cueing, but error rates. If both effects simply add up, the color change would reduce the gradual increase of contextual cueing and the color change would increase error rates. However, if both effects interact, the result would not obligatory be a disappearance of contextual cueing. Because distractors are defined by their color and orientation, a double change in old configuration trials would affect their identity (rather than a mere attribute); consequently, a dual color and orientation change might generate a search array with completely new objects that still occupy the same locations in the display. In the case of dual changes, participants can only rely on the spatial configuration, the only available cue conveying information regarding the target location. As already reported by Chun and Jiang (1998), a whole change of the distractors identity does not abolish the contextual cueing effect. By implication, it may be claimed that a color-orientation change therefore corresponds or is equal to an identity change.

7.6.1. Method

Participants. Fourteen observers (twelve female and 2 male) took part to Experiment 4. All were students at the University of Fribourg. They received course credits. They were aged between 18 and 25 years (median = 20.5 years). All observers had normal or a corrected to normal vision, including normal color vision.

Design, procedure and stimuli. The design of Experiment 4 was similar to the design of the feature change Experiments 3 and 4. In Experiment 4, the color and orientation of all distractors changed in the middle of the experiment (block 13 of 24); as in Experiment 2, Ls that were 0°-tilted in the first half of experiment were changed to a 180°-tilt for the rest of the second half (90°-tilted Ls to 270° -tilted, 180°-tilted Ls to 0°, and 270°-tilted Ls to 90°), and, as in Experiment3, elements that were red in the first half of experiment turned into green for the rest of the second half, analogously, green into blue, blue into yellow and yellow into red.

Apparatus and setting. Apparatus and setting were the same as in Experiment 1.

7.6.2. Results and discussion

Error rates were, on average, at 1.6 % (*SD* = 0.9 %) for old configuration trials and 1.8 % (*SD* = 1.3 %) for new configuration trials (non-significant difference: $t(13) = -.89$, $p > .10$). Rates of extremely slow responses corresponded to 0.32 % (*SD* = 0.51 %) of old configuration trials and 0.72 % (*SD* = 1.30 %) of new configurations trials, while the outliers corresponded to 2.08 % (*SD* = 0.62 %) and 2.38% (*SD* = 0.92 %) of old and new configurations, respectively.

Figure 7.9 represents the RTs in function of the configuration in each block of Experiment 4. The configuration (old, new) x block repeated-measures ANOVA of RTs showed significant main effects of configuration ($F(1,13) = 17.15$, $MS_e = 17036.72$, $p < .001$; Huynh-Feldt-corrected degrees of freedom) and block ($F(12.78,166.17) = 4.27$, $MS_e = 14977.20$, $p < .001$, Huynh-Feldt-corrected degrees of freedom). The main effect of block was accompanied by a significant linear effect ($F(1,13) = 15.48$, $MS_e = 36809.38$, $p < .001$) and a tendency of a significant quadratic effect ($F(1,13) = 4.40$, $MS_e = 9132.39$, $p = .056$). The interaction did not reach statistical significance ($F(16.69,216.97) = 1.05$, $MS_e = 6894.50$, $p > .10$).

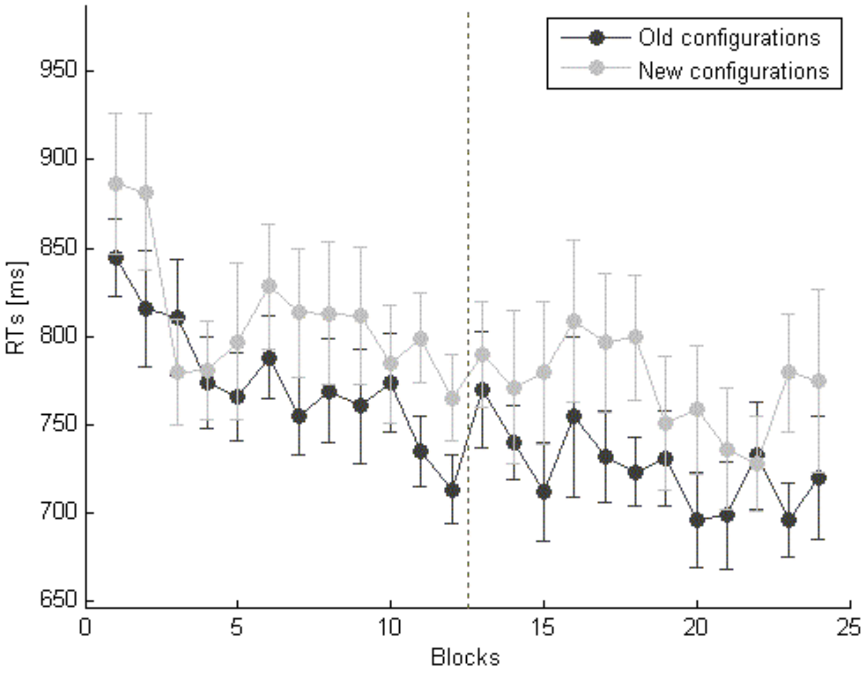

Figure 7.9. Mean RTs (and standard errors) per configuration and block in Experiment 4. The dark grey line represents RTs for old configuration trials, whereas the light grey line stands for the RTs for the new configuration trials. The dashed line represents the manipulation location.

After regrouping blocks into six epochs, a two-way (factors: configuration x epoch) repeated-measures ANOVA showed similar results as in the previous Experiment 3. The ANOVA revealed significant main effects of epoch ($F(2.45,31.89) = 9.19$, $MS_e = 6157.35$, $p < .001$, Huynh-Feldt-corrected degrees of freedom) and configuration ($F(1,13) = 17.15$, $MS_e = 4259.19$, $p < .001$, Huynh-Feldt-corrected degrees of freedom). After summarizing blocks into epochs, the interaction between configuration and block remained non-significant ($F(4.13,53.73) = .75$, $MS_e = 1452.88$, $p > .10$, Huynh-Feldt-corrected degrees of freedom). Furthermore, running the same analyses, error rater were shown to be influenced neither by the configuration ($F(1,13) = .79$, $MS_e = .61$, $p > .10$), nor epoch ($F(5,65) = 1.77$, $MS_e = .53$, $p > .10$; interaction: $F(5,65) = .67$, $MS_e = .62$, $p > .10$).

Although epoch and configuration did not interact, RTs for old configurations were smaller than for new configurations and both RT functions decreased as of function of the epoch. This suggests that changing the color and orientation of all elements in the middle of the experiment did not affect the contextual cueing effect at the level of the whole experiment.

The effect of the manipulation effect was, however, checked as in previous Experiments 2 and 3.

Table 7.5

Mean RTs (ms) for new and old configurations per epoch in Experiment 4 (standard deviations in parentheses), F values of the simple contrast between old and new configurations.

	Epoch 1	**Epoch 2**	**Epoch 3**	**Epoch 4**	**Epoch 5**	**Epoch 6**
New configuration	832.37	813.08	790.18	787.43	776.56	754.59
	(109.84)	(129.01)	(87.58)	(116.35)	(120.87)	(122.12)
Old configuration	811.43	769.61	745.81	744.33	720.79	712.04
	(89.85)	(81.47)	(74.90)	(101.43)	(82.36)	(94.64)
F(1,13)	2.85	5.18	13.18	5.08	16.35	7.48
p	.115	.040	.003	.042	.001	.017

Within-experiment analyses of the color and orientation manipulation. A two-way (factors configuration x manipulation) repeated-measures ANOVA of the RTs showed that both main effects of manipulation (*F*(1,13) = 12.17, MS_e = 2274.55, *p* < .01, Huynh-Feldt-corrected degrees of freedom) and configuration (*F*(1,13) = 17.15, MS_e = 1419.73, *p* < .001, Huynh-Feldt-corrected degrees of freedom) were significant. The interaction between the factors was not significant (*F*(1,13) = 1.19, MS_e = 348.36, *p* > .10, Huynh-Feldt-corrected degrees of freedom). Multiple comparisons revealed that the target was detected faster in old than in new configuration trials in both halves of the experiment (old configurations before manipulation: *M* = 775.6 ms, *SD* = 79.0 ms; new configurations before manipulation: *M* = 811.9 ms, *SD* = 98.5 ms; *F*(1,13) = 13.31, *p* < .01; old configurations after manipulation: *M* = 725.7 ms, *SD* = 88.8 ms; new configurations after manipulation: *M* = 772.9 ms, *SD* = 117.0 ms; *F*(1,13) = 14.45, *p* < .01). Further, although the difference between old and new configurations after the middle of the experiment (*M* = 47.1 ms, *SD* = 46.4 ms) was numerically larger than before the mid-experiment feature manipulation (*M* = 36.3 ms, *SD* = 37.2 ms), they did not differ significantly from each other (*t*(13) = -1.09, *p* > .10). Furthermore, the manipulation did not affect error rates (configuration: *F*(1,13) = .79, MS_e = .57, *p* > .10; manipulation: *F*(1,13) =

3.18, $\mathrm{MS_e} = .50$, $p = .098$; interaction: $F(1,13) = .12$, $\mathrm{MS_e} = 1.11$, $p > 10$, all corrected with Huynh-Feldt degrees of freedom).

Comparing the epochs just before and after the mid-experiment manipulation for each configuration revealed a different pattern of results as the previous analysis; namely a significant main effect of configuration ($F(1,13) = 18.51$, $\mathrm{MS_e} = 1446.70$, $p < .001$), but neither the main effect of epoch ($F(1,13) = .04$, $\mathrm{MS_e} = 1577.97$, $p > .10$), nor a significant interaction ($F(1,13) = .003$, $\mathrm{MS_e} = 2160.16$, $p > .10$). Finally, although there was a tendency of lower error rates in old configuration trials ($M = 0.75$ % $SD = 0.61$ %) relative to new configuration trials ($M = 1.07$ %, $SD = 0.83$ %; $F(1,13) = 3.91$, $\mathrm{MS_e} = .37$, $p = .069$, Huynh-Feldt corrected degrees of freedom), no statistically significant difference between error rates before and after the manipulation was observed ($F(1,13) = .02$, $\mathrm{MS_e} = 1.17$, $p > .10$, Huynh-Feldt corrected degrees of freedom). The interaction was not significant, either ($F(1,13) = .51$, $\mathrm{MS_e} = .32$, $p > .10$, Huynh-Feldt-corrected degrees of freedom).

Between-experiments analyses of the color and orientation manipulation. A comparison of the contextual cueing effect of Experiments 1 and 4 before and after the manipulation showed a significant increase of the contextual cueing effect after the manipulation. A two-way (factors manipulation x experiment) ANOVA revealed that the amount of contextual cueing grew significantly after the manipulation (before manipulation: $M = 31.9$ ms, $SD = 50.1$ ms, after manipulation: $M = 52.2$ ms, $SD = 44.1$ ms; $F(1,28) = 6.84$, $\mathrm{MS_e} = 847.39$, $p < .05$, Huynh-Feldt corrected degrees of freedom). No significant difference between Experiments 1 and 4 was observed (Experiment 1: $M = 42.4$ ms, $SD = 43.2$ ms, Experiment 2: $M = 41.7$ ms, $SD = 43.2$ ms; $F(1,28) = .002$, $\mathrm{MS_e} = 3728.15$, $p > .10$). Although the interaction between experiment and manipulation did not reach the statistical significance ($F(1,28) = 1.37$, $\mathrm{MS_e} = 847.39$, $p > .10$), multiple comparisons revealed that contextual cueing increased significantly after the manipulation in Experiment 1 (before manipulation: $M = 28.2$ ms, $SD = 60.3$ ms, after manipulation: $M = 56.7$ ms, $SD = 43.0$ ms; $F(1,28) = 7.68$, $p < .01$), whereas there was a non-significant in Experiment 4 (before manipulation: $M = 36.3$ ms, $SD = 37.2$ ms, after manipulation: $M = 47.1$ ms, $SD = 46.4$ ms; $F(1,28) = .98$, $p > .10$).

As can be seen in Figure 7.10, the analysis of the contextual cueing slope after the manipulation demonstrated that, despite an almost flat slope in Experiment 4 ($M = -.27$, $SD = 41.19$), slopes in Experiment 1 ($M = 15.48$ ms, $SD = 30.33$ ms) and 4 were statistically comparable ($t(28) = .24$, $p > .10$). A similar observation was made in the comparison between the slopes of epochs 3 to 4 Experiments and 2 (Experiment 1: *M* = -1.27 ms, *SD* = 92.96 ms, Experiment 4: *M* = 9.18 ms, *SD* = 59.34 ms; *t*(28) = .71, *p* > .10).

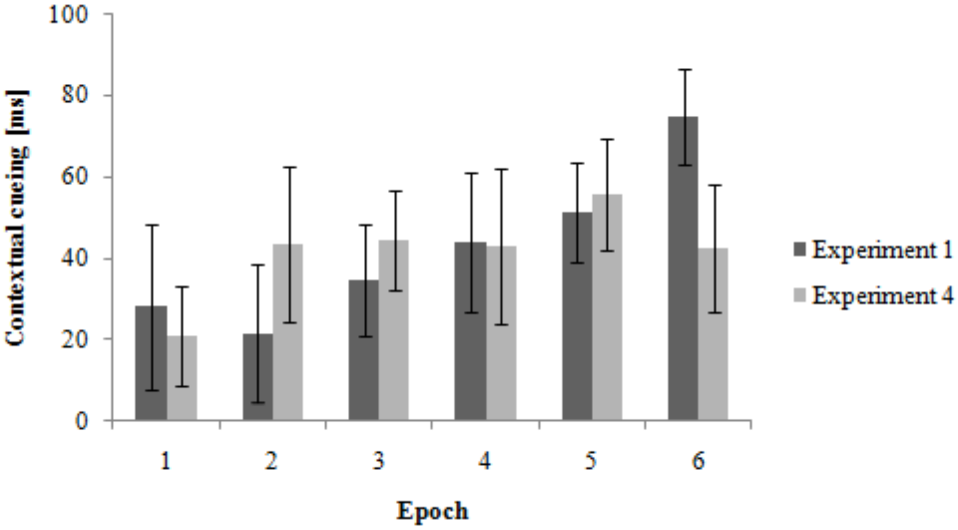

Figure 7.10. Contextual cueing effect in Experiment 1 and 4. Error bars represent standard errors.

In contrast to Experiment 2 in an effect of the color change on the development of contextual cueing was clearly demonstrated, RTs in Experiment 4 were not affected by the dual color and orientation manipulation. A single color change can disturb the contextual cueing effect, whereas a conjunctive feature change acts in a similar way as a change of the distractor identity (i.e., similar to the manipulation used by Chun and Jiang, 1998, Experiment 2) and did not affect contextual cueing. As already mentioned above, both object (feature) and spatial cueing seem to be involved in the generation of the contextual cueing effect (see Endo & Takeda, 2002, 2004) but object (feature) and spatial cues differently affect the implicit memory they generate. The present results suggest that, after a color change, participants continue using both spatial and object cueing, but, because object cueing becomes less reliable after the change, the interaction between the two types of cue is skewed and distorts the contextual cueing effect. However, after a complete feature change, because object cueing is no more reliable any longer, participants seem to rely exclusively on spatial cueing. In this case, contextual cueing is not affected (as reported by Chun and Jiang, 1998).

7.7. Experiment 5: Hue change

Experiments 2 to 4 demonstrate that different object features do not all play the same role in the development of the contextual cueing effect. Distractor color, but not orientation, can efficiently cue the target position. This observation is coherent with results observed by Huang (2006) showing that a color change can cancel out the contextual cueing effect. In addition, Huang’s study provides evidence that two aspects of color, namely hue and luminance, can serve as cues contributing to the identification of the target location. However, Huang did not examine which component of the color gives raise to the disruption of contextual cueing in a color change experiment. The two following Experiments 5 and 6 were designed to answer this question. In analogy to the color and orientation changes in the previous experiments of this study, a hue change was introduced in the middle of Experiment 5, in which all the colors had the same luminance; in Experiment 6, a luminance change was applied to all elements presenting the same hue.

7.7.1. Method

Participants. Sixteen observers (fourteen female and two male) took part in Experiment 5. All were students at the University of Fribourg. They received course credits for participation. They were aged between 19 and 42 years (median = 21 years). All observers had normal or corrected to normal vision, including normal color vision.

Design, procedure and stimuli. The design of Experiment 5 was the design of Experiment 2, with the exception that all color hues were isoluminant (5cd/m2), including the background. The hue of elements changed in the middle of the experiment.

Apparatus and setting. Apparatus and setting were the same as in the preceding experiments.

7.7.2. Results and discussion

The same analysis procedure as in previous experiments was used. (No old configuration trials needed to be excluded because they had facilitated detection.) Error rates were, on average 2.6 % (*SD* = 1.6%) for old configuration trials and 2.1% (*SD* = 1.4%) for new configuration trials (non-significant difference: $t(13) = 1.64$, $p > .10$). Extremely slow responses corresponded to 0.5 % (*SD* = 0.9 %) of old configuration trials and 1.0% (*SD* = 0.8 %) of new configurations trials, outliers corresponded 2.3 % (*SD* = 0.9 %) and 1.9 % (*SD* = 0.6 %) of old and new configuration trials, respectively. The data sets of two observers whose overall error rates exceeded 10% were also discarded from analysis.

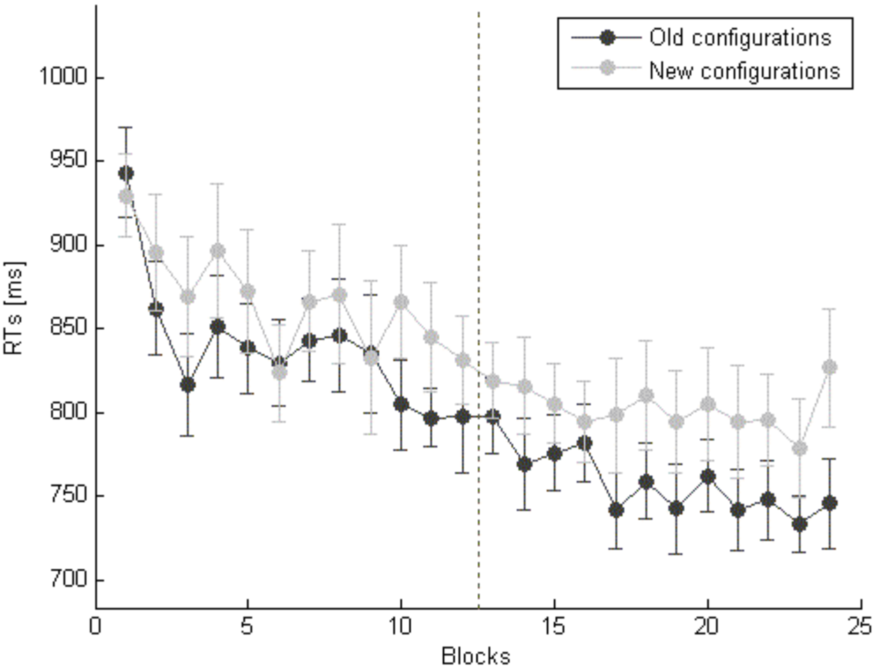

Figure 7.11. Mean RTs (and standard errors) per configuration and block in Experiment 5. The dark grey line represents RTs for old configuration trials, whereas the light grey line stands for the RTs for the new configuration trials. The dashed line represents the manipulation location.

Figure 7.11 displays RTs for each configuration and each block of Experiment 5. The block x configuration repeated measures ANOVA of RTs showed significant main effects of configuration (*F*(1,13) = 7.71, MS_e = 28731.73, *p* < .05, Huynh-Feldt corrected degrees of freedom) and block (*F*(18.70,243.14) = 6.81, MS_e = 9946.12, *p* < .001, Huynh-Feldt corrected degrees of freedom). The main effect of block was accompanied by significant linear (*F*(1,13) = 58.63, MS_e = 18076.21, *p* < .001) and quadratic effects (*F*(1,13) = 5.44, MS_e = 10456.09, *p* < .05, see Figure 7.11). However, the interaction between factors did not reach significance (*F*(19.70,256.09) = 1.26, MS_e = 7427.92, *p* > .10). After regrouping blocks into six epochs (see Table 7.8), a two-way (factors: configuration – epoch) repeated-measures ANOVA revealed similar results as the block-based configurations analysis. The main effect of configuration (*F*(1,13) = 7.71, MS_e = 7182.91, *p* < .05, Huynh-Feldt corrected degrees of freedom) and epoch ($F(5,65) = 19.09$, $MS_e = 2841.64$, $p < .001$) were significant, whereas the factor did not interact ($F(5,65) = .99$, $MS_e = 1495.69$, $p > .10$). Error analyses showed no significant main effects or interaction (configuration: $F(1,13) = 2.70$, $MS_e = .97$, $p > .10$, Huynh-Feldt corrected degrees of freedom; epoch: $F(3.94,51.17) = 1.04$, $MS_e = 1.25$, $p > .10$; interaction: $F(5,65) = .50$, $MS_e = 1.09$, $p < .10$).

Table 7.6

Mean RTs (ms) for new and old configurations per epoch in Experiment 5 (standard deviations in parentheses), F values of the simple contrast between old and new configurations.

	Epoch 1	**Epoch 2**	**Epoch 3**	**Epoch 4**	**Epoch 5**	**Epoch 6**
New configuration	897.64	858.33	843.67	808.82	802.31	799.06
	(98.51)	(102.82)	(93.18)	(64.75)	(100.34)	(93.72)
Old configuration	868.43	839.50	808.67	781.39	751.63	742.34
	(77.36)	(85.16)	(72.44)	(74.88)	(66.44)	(65.62)
F(1,13)	2.89	1.04	3.43	2.23	7.27	7.83
p	.113	.325	.087	.160	.018	.015

Although the factors configuration and epoch did not reveal a significant interaction, Experiment 5 provides evidence that a single color hue change in the middle of the experimental session does not alter the development of contextual cueing. To provide further support for this result, the effect of the hue manipulation was examined with the same procedure as used in previous experiments

Within-experiment analyses of the color hue manipulation. Changing the hue of all elements in the middle of the experiment when all hues were isoluminant seemed not to disturb the contextual cueing effect. A two-way (factors: manipulation x configuration) repeated-measures ANOVA of the RTs for the whole Experiment 5 showed that both main effects of manipulation ($F(1,13) = 54.93$, $MS_e = 1313.15$, $p < .001$, Huynh-Feldt corrected degrees of freedom) and configuration ($F(1,13) = 7.71$, $MS_e = 2394.31$, $p < .05$, Huynh-Feldt corrected degrees of freedom) were significant. Despite a non-significant interaction ($F(1,13) = 2.75$, $MS_e = 379.45$, $p > .10$, Huynh-Feldt corrected degrees of freedom), multiple comparisons revealed that old and new configurations are statistically distinguishable after the medexperiment. No difference in the first half of the experiment (*F*(1,13) = 3.69, *p* = .077) for old (*M* = 838.9 ms, *SD* = 72.0 ms) and new configurations (*M* = 866.5 ms, *SD* = 85.0 ms), were observed, in the second half of the experiment, old configuration trials (*M* = 758.5 ms, *SD* = 62.6 ms) were detected significantly faster than new configurations (*M* = 803.4 ms, *SD* = 80.0 ms; *F*(1,13) = 10.72, *p* < .01). Error rates were modulated neither by the manipulation (*F*(1,13) = 2.61, MS_e = 1.32, *p* < .10, Huynh-Feldt corrected degrees of freedom), nor by the configuration (*F*(1,13) = 2.7, MS_e = .90, *p* < .10, Huynh-Feldt corrected degrees of freedom). The interaction was also not significant (*F*(1,13) = .01, MS_e = 1.09, *p* > .10)

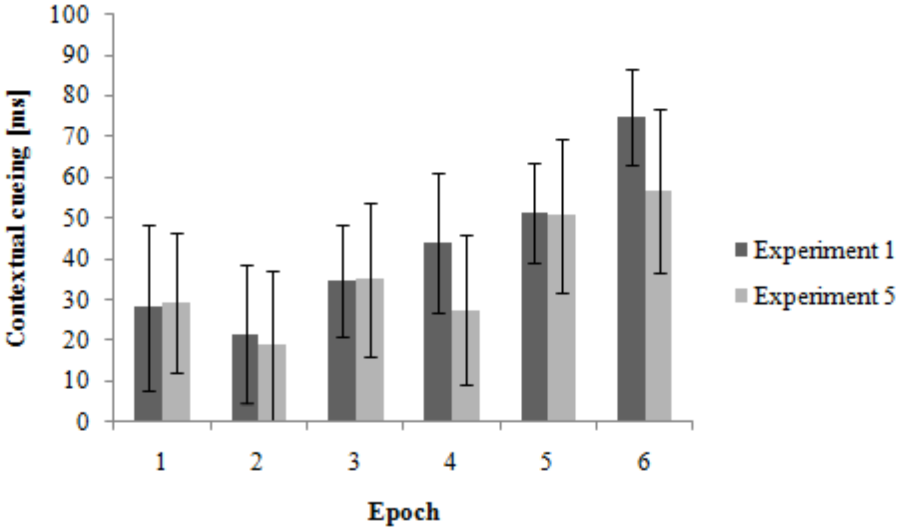

Figure 7.12. Contextual cueing effect in Experiment 1 and 5. Error bars represent standard errors.

Comparing the two epochs before (epoch 3) and after (epoch 4) the middle of the experiment for each configuration type revealed results similar to those obtained in the previous Experiment 4, namely a significant main effect of the factor epoch (*F*(1,13) = 5.33, MS_e = 2532.95, *p* < .05), a marginally significant main effect of the factor configuration (*F*(1,13) = 4.00, MS_e = 3410.35, *p* = .067) and a non-significant interaction effect (*F*(1,13) = .14, MS_e = 1459.95, *p* > .10; see Table 7.6 for the descriptive data). Finally the hue change at mid-experiment did not modify error rates of the whole experiment (configuration: *F*(1,13) = 2.70, MS_e = .899, *p* > .10; manipulation: *F*(1,13) = 2.61, MS_e = 1.32, *p* > .10; interaction: *F*(1,13) = .01, MS_e = 1.09, *p* > .10, all Huynh-Feldt corrected degrees of freedom); there was no effect on error rates between epochs 3 and 4 either (configuration: *F*(1,13) = 1.43, MS_e = 1.80, *p* >

.10; epoch: *F*(1,13) = 4.12, MS_e = 1.11, p = .063; interaction: *F*(1,13) = 0, MS_e = .85, *p* > .10, all corrected with Huynh-Feldt degrees of freedom).

Between-experiments analyses of the hue manipulation. Experiments 1 and 5 were not dissociable at a global analysis level. A two-way (factors: manipulation x experiment) ANOVA revealed only a significant main effect of manipulation (*F*(1,28) = 8.94, MS_e = 876.45, *p* < .01, Huynh-Feldt corrected degrees of freedom), reflecting a significant increase of contextual cueing after the manipulation (before manipulation: *M* = 27.9 ms, *SD* = 56.4 ms, after manipulation: *M* = 51.2 ms, *SD* = 46.6 ms). No significant difference between experiments was observed (Experiment 1: *M* = 42.4 ms, *SD* = 48.1 ms, Experiment 5: *M* = 36.3 ms, *SD* = 49.8 ms; *F*(1,28) = .12, MS_e = 4633.11, *p* > .10). Although the interaction between experiment type and manipulation did not reach significance (*F*(1,28) = .54, MS_e = 876.45, *p* > .10), multiple comparisons revealed than the contextual cueing increased significantly after the manipulation in Experiment 1 (before manipulation: *M* = 28.17, *SD* = 60.25, after manipulation: *M* = 56.70, *SD* = 42.97; *F*(1,28) = 7.43, *p* < .05), whereas this increase did not reach the significance level in Experiment 5 (before manipulation: *M* = 27.67, *SD* = 53.93, after manipulation: *M* = 44.94, *SD* = 51.37; *F*(1,28) = 2.38, *p* > .10).

Comparison of the slopes of the contextual cueing effect after the manipulation were comparable in Experiment 1 (*M* = 15.48, *SD* = 30.33) and Experiment 5 (*M* = 14.64, *SD* = 46. 62; *t*(28) = .06, *p* > .10). Finally, at a local level, although the slope between epochs 3 to 4 was, on average, positive in Experiment 1 (*M* = 9.18, *SD* = 59.34) and negative in Experiment 5 (*M* = -7.56, *SD* = 76.42), they did not diverge significantly (*t*(28) = .68, *p* > .10).

Although a (non-significant) local reduction of the contextual cueing in epoch 4 (see Figure 7.12) was revealed, the results obtained in Experiment 5 are similar to those obtained in Experiment 1, suggesting that the alteration of the contextual cueing found in the color change Experiment 2 seems not to be due to a change in the color hue. The alternative explanation for the findings of Experiment 2 is that the effect is could be due to the change of luminance. To investigate this issue, all objects of Experiment 6 were drawn in the same hue (i.e., green) but were different with respect to their luminance. The object luminance changed in the middle of the experimental session.

7.8. Experiment 6: Luminance change

7.8.1. Method

Participants. Twelve observers (ten female and two male) took part in Experiment 6. All were students at the University of Fribourg. They received course credits or were paid at a rate of CHF 5. They were aged between 19 and 34 years (median = 20 years). All observers had normal or corrected to normal vision, including normal color vision. The data sets of two observers whose overall error rates exceeded 10% were also discarded from analysis.

Design, procedure and stimuli. In order to examine the impact of a luminance change without modifying the number of object-defining features, an equal number of elements were colored with one of the exponential luminance values of green (respectively, 4, 8, 16 and 32 cd/m2). The background was set to a 12cd/m2 grey. From block 13, all elements changed their luminance, i.e., the luminance value of the 32cd/m2 elements turned into 8 cd/m2 (the 16cd/m2 value into a 4cd/m2, the 8cd/m2 value into a 32cd/m2, and the 4cd/m2 value into a 16cd/m2).

Apparatus and setting. Apparatus and setting were the same as in preceding experiments.

7.8.2. Results and discussion

The same analysis procedure as in previous experiments was used. (No old configuration trials needed to be excluded because they facilitated target detection.) Error rates were on average 1.6 % (*SD* = 1.2 %) for old configuration trials and 1.9 % (*SD* = 2.2 %) for new configuration trials (no significant difference: $t(9) = .91$, $p > .10$). Extremely slow responses corresponded to 0.31 % (*SD* = 0.53 %) of old configuration trials and 1.60 % (*SD* = 1.79 %) of new configuration trials; outlier rate corresponded to 2.36 % (*SD* = 0.95 %) and 1.91 % (*SD* = 0.68 %) of old and new configurations, respectively. Based on the maximal 10 % of invalid trials criteria (see Experiment 4), two participants were excluded.

Figure 7.13 shows RTs for each configuration and each block of Experiment 6. As in previous experiment, a two-way repeated-measures ANOVA on RTs revealed significant main effects of the configuration ($F(1,9) = 8.51$, $MS_e = 37798.61$, $p < .05$, Huynh-Feldt-corrected degrees of freedom) and block ($F(23, 207) = 5.37$, $MS_e = 954.38$, $p < .001$, Huynh-Feldt-corrected degrees of freedom). The effect of block was accompanied by significant linear (*F*(1,9) = 33.63, MS_e = 30238.29, *p* < .001) and quadratic effects (*F*(1,9) = 6.11, MS_e = 7118.19, *p* < .05). The interaction between factors did not reach significance (*F*(23,207) = 1.27, MS_e = 5833.76, *p* > .10, Huynh-Feldt-corrected degrees of freedom).

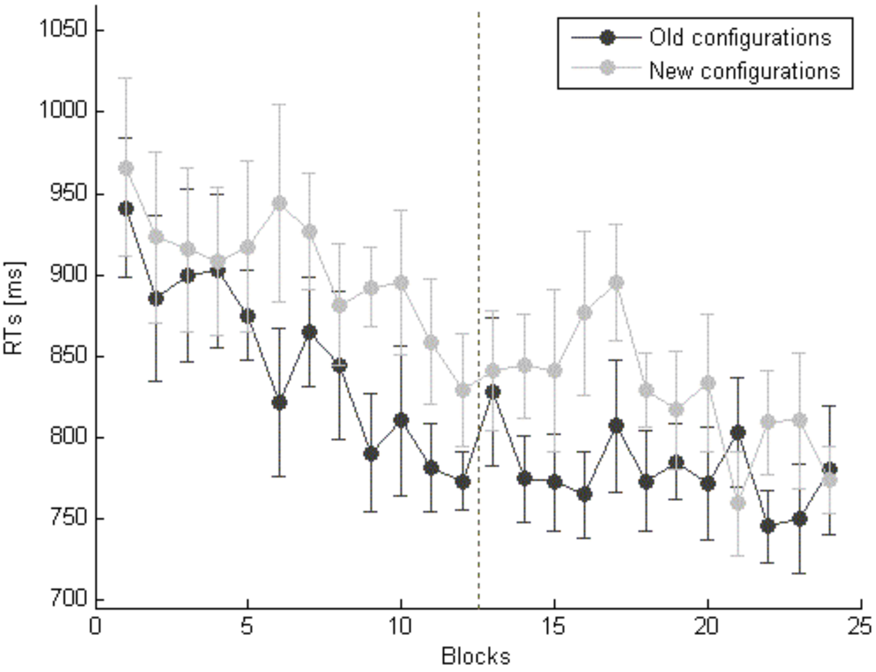

Figure 7.13. Mean RTs (and standard errors) per configuration and block in Experiment 6. The dark grey line represents RTs for old configuration trials, whereas the light grey line stands for the RTs for the new configuration trials. The dashed line represents the manipulation location.

After regrouping blocks into six epochs (see Table 7.7), a two-way (factors: configuration – epoch) repeated-measures ANOVA revealed slightly different results than the block-based analysis. The main effects of configuration (*F*(1,9) = 8.51, MS_e = 9449.65, *p* < .05, Huynh-Feldt-corrected degrees of freedom) and epoch (*F*(5,45) = 15.86, MS_e = 3308.55, *p* < .001) were significant, and the interaction tended to be significant (*F*(5,45) = 2.33, MS_e = 1402.88, *p* = .057). A configuration x epoch repeated-measures ANOVA showed a significant main effect of epoch (*F*(5,45) = 3.19, MS_e = .34, *p* < .05). The main effect of configuration (*F*(1,9) = .82, MS_e = 1.23, *p* > .10, Huynh-Feldt-corrected degrees of freedom) and the configuration x epoch interaction were not significant (*F*(5,70) = 1.08, MS_e = .39, *p* < .10). Multiple comparisons (see Table 7.7) revealed that the contextual effect grew significantly until epoch 3, remained stable in epochs 4 and 5, in epoch 6, although RTs of old configuration trials were smaller than in new configuration trials, the difference between configurations was not significant.

Table 7.7

Mean RTs (ms) for new and old configurations per epoch in Experiment 6 (standard deviations in parentheses), F values of the simple contrast between old and new configurations.

	Epoch 1	**Epoch 2**	**Epoch 3**	**Epoch 4**	**Epoch 5**	**Epoch 6**
New configuration	928.38	917.34	868.63	850.26	843.50	787.95
	(132.28)	(111.94)	(71.14)	(111.20)	(84.56)	(80.46)
Old configuration	907.26	851.49	788.71	784.85	783.84	769.27
	(142.70)	(100.07)	(93.20)	(87.25)	(90.87)	(75.21)
F(1,9)	.64	14.82	40.39	4.61	4.93	.71
p	.444	.004	.000	.060	.054	.423

The error rates were analyzed with a two-way (factors: configuration x epoch) repeated-measures ANOVA. Results showed no significant main effect of configuration (*F*(1,9) = .82, MS$_e$ = 1.23, *p* > .10, Huynh-Feldt-corrected degrees of freedom), as well as a non-significant interaction (*F*(5,45) = .70, MS$_e$ = .72, *p* > .10). However, a significant main effect of epoch was observed (*F*(4,45) = 3.20, MSe = .34, *p* > .05), but multiple comparisons of the levels of the factor epoch did not reveal any significant difference (all *p* > .10).

Altogether, these results show that a luminance change does not modulate the contextual cueing effect. To confirm this observation, the same procedure as in previous experiments was applied.

Within-experiment analyses of the luminance manipulation. Changing the luminance of all elements in the middle of the experiment seemed to affect the contextual cueing effect at the level of the whole experiment. A two-way (factors: manipulation x configuration) repeated-measures ANOVA of the RTs of the whole experiment showed that both main effects of manipulation (*F*(1,9) = 30.98, MS$_e$ = 1752.75, *p* < .001, Huynh-Feldt corrected degrees of freedom) and configuration (*F*(1,9) = 8.51, MS$_e$ = 3149.88, *p* < .05, Huynh-Feldt corrected degrees of freedom) were significant. Despite a non-significant interaction effect (*F*(1,9) =

.27, $MS_e = 544.04$, $p > .10$, Huynh-Feldt-corrected degrees of freedom), multiple comparisons revealed that old and new configurations are significantly different only before the mid-experiment manipulation. In the first half of the experiment, targets in old configuration trials (*M* = 849.15 ms, *SD* = 107.99 ms) were detected significantly faster than new configuration trials (*M* = 904.78 ms, *SD* = 100.29 ms; $F(1,9) = 12.15$, $p < .01$), whereas no difference was found in the second half of the experiment ($F(1,9) = 4.74$, $p = .057$) for old (*M* = 779.32 ms, *SD* = 77.96 ms) or new configurations (*M* = 827.24 ms, *SD* = 84.86 ms). In addition, a manipulation x configuration repeated-measures ANOVA on error rates revealed only a tendency of a significant main effect of the factor manipulation ($F(1,9) = 3.45$, $MS_e = .378$, $p = .096$); slightly more errors were made after (*M* = 1.58 %, *SD* = 1.56 %) than before the manipulation (*M* = 1.22 %, *SD* = 1.10 %). Neither the main effect of configuration ($F(1,9) = .82$, $MS_e = 1.23$, $p > .10$; Huynh-Feldt-corrected degrees of freedom), nor the interaction were significant ($F(1,9) = .70$, $MS_e = .72$, $p > .10$). Thus, error rates were not modulated by the luminance manipulation.

Comparing epochs before and after the mid-experiment luminance manipulation for old and new configurations revealed a different pattern of results relative to those obtained in the previous Experiment 5. A significant main effect of configuration ($F(1,9) = 16.59$, $MS_e = 3183.31$, $p < .01$; Huynh-Feldt-corrected degrees of freedom) revealed that targets were detected faster in old configuration trials (*M* = 786.78, *SD* = 83.78) than in new configuration trials (*M* = 859.45 ms, *SD* = 87.23 ms). Neither the main effect of manipulation ($F(1,9) = .56$, $MS_e = 2223.64$, $p < .10$), nor the interaction ($F(1,9) = .23$, $MS_e = 2244.99$, $p > .10$), were significant. However, multiple comparisons showed that RTs for old configuration trials differed from those for the new configuration trials before the mid-experiment manipulation. In the first half of the experiment, the target was detected significantly faster in the old configuration trials (*M* = 788.71 ms, *SD* = 93.20 ms) than in the new configuration trials (*M* = 868.63 ms, *SD* = 71.14 ms, $F(1,9) = 40.32$, $p < .001$), this was no longer the case in the second half of the experiment (old configuration: *M* = 784.85 ms, *SD* = 87.25 ms, new configuration: *M* = 850.26, *SD* = 111.20, $F(1,9) = 4.61$, $p = .060$). No difference in the error rate was observed before and after the manipulation (manipulation: $F(1,9) = 2.19$, $MS_e = .56$, $p > .10$; configuration: $F(1,9) = .53$, $MS_e = 1.18$, $p > .10$; interaction: $F(1,9) = 1.83$, $MS_e = .67$, $p > .10$).

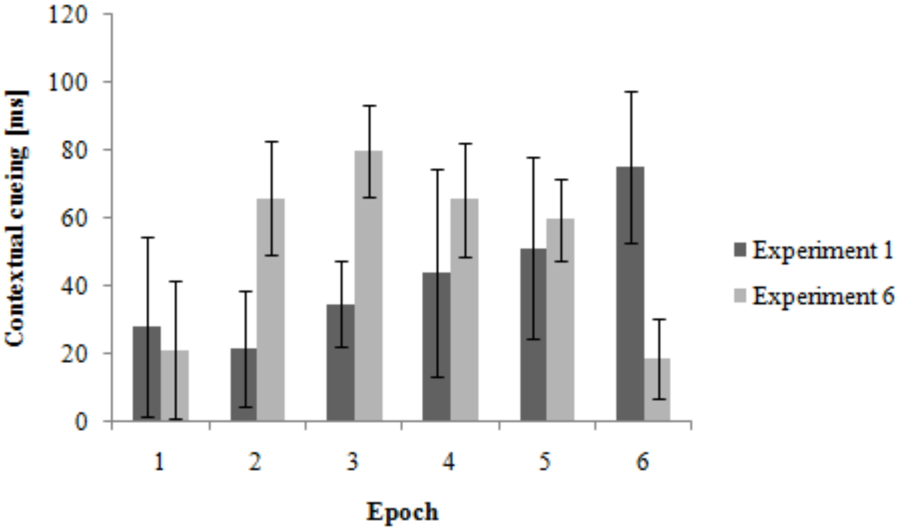

Figure 7.14. Contextual cueing effect in Experiment 1 and 6. Error bars represent standard errors.

*Between-experiments analyses of the luminance manipulation***.** The contextual cueing effect was compared between Experiments 1 and 6 as a function of the manipulation at a level of the entire Experimental 6 with a two-way (factors: manipulation x experiment type) mixed-measures ANOVA. Results showed that neither the main effect of manipulation ($F(1,24) = 1.31$, $MS_e = .26$, $p > .10$; Huynh-Feldt-corrected degrees of freedom) and nor of experiment ($F(1,24) = .21$, $MS_e = 5173.88$, $p > .10$) were significant. The interaction, however, was marginally significant ($F(1,24) = 3.96$, $MS_e = 119.49$, $p = .058$; Huynh-Feldt-corrected degrees of freedom). Multiple comparison showed that, as expected, contextual cueing increased significantly from the beginning (M = 28.17 ms, *SD* = 60.25 ms) to the end of Experiment 1 (*M* = 56.70 ms, *SD* = 42.97 ms; $F(1,24) = 6.39$, $p < .05$), in contrast, contextual cueing decreased in the second half of Experiment 6 slightly but not in a significantly (before manipulation: *M* = 55.63 ms, *SD* = 50.47 ms; after manipulation: *M* = 47.92 ms, *SD* = 69.58 ms; $F(1,24) = .29$, $p > .10$).

The analysis of the slope after the mid-experiment manipulation was also affected by the reduced contextual cueing in epoch 6 of Experiment 6, reflected by a negative slope (*M* = -23.37 ms, *SD* = 45.51 ms), whereas the slope in Experiment 1 was positive (*M* = 15.48 ms, *SD* = 30.33 ms). Further, both slopes diverged significantly ($t(24) = 2.62$, $p < .05$). Finally, although the slope between epochs 3 and 4 in Experiment 1 was positive (*M* = 9.18 ms, *SD* =

59.34 ms) and negative in Experiment 6 (*M* = -14.51 ms, *SD* = 94.76 ms), they did not differ significantly ($t(13.47) = .49$, $p > .10$).

Despite a drastic reduction of the contextual cueing effect in epoch 6 of Experiment 6, the contextual cueing does not seem to be altered by a luminance change. The decrease of contextual cueing in the last epoch has its origin not in an increase of RTs in old configuration trials, but in a drop of RTs in new configuration trials, reinforcing the assumption that the luminance itself cannot efficiently contribute to the cueing of the target location.

Altogether, the findings of Experiments 5 and 6 reveal that a change in one of the color components cannot explain the disappearance of the contextual cueing effect found in Experiment 2, leading to the conclusion that results of Experiment 2 are highly probably caused by an interaction of both color hue and luminance.

7.9. Experiment 7: Size change

Preceding experiments demonstrated that a change in the color feature that is not directly implicated in the task, as orientation is, can disrupt the contextual cueing effect. The two Experiments 7 and 8 investigated whether another search-irrelevant feature, such as size, can efficiently cue the target position. Experiment 7 introduced search items of four different sizes in the search display. As in previous experiments, the size changed in the middle of the experimental session.

7.9.1. Method

Participants. Sixteen observers (fifteen female and one male) took part in Experiment 7. All were students at the University of Fribourg. They received course credits for participation. They were aged between 18 and 23 years (median = 20 years). All observers had a normal or a corrected to normal vision, including normal color vision.

Design, procedure and stimuli. In order to examine the impact of a size change without modifying the number of object-defining features (namely color and orientation in previous experiments), all elements were green (RGB: 0, 200, 0). Furthermore, keeping the same orientation for each element would have simplified the search. An equal number of objects had the approximate size of 2.29° (size 1), 1.72° (size 2), 1.15° (size 3) and 0.57° of visual angle (size 4). In the middle of the experiment (in block 13), the size of the objects changed, namely, objects of size 1 changed to size 3 and objects of size 2 changed to size 4, while objects of size 3 and 4 had respectively changed to size of 1 and 2 for the remaining part of the experiment. Finally, all objects had a thickness of 0.34°of visual angle that remained constant during the whole experiment.

Apparatus and setting. Apparatus and setting were the same as in preceding experiments.

7.9.2. Results and discussion

The same analysis procedure as in previous experiments was used. (No old configuration trials needed to be excluded because they facilitated target detection.) Error rates were in average 1.09 % (*SD* = 1.07 %) for old configuration trials and 0.81 % (*SD* = 0.89 %) for new configuration trials (significant difference: $t(14) = 2.18$, $p < .05$). The extremes slow responses represented 1.04 % (*SD* = 1.18 %) of old configuration trials and 2.11 % (*SD* = 1.57 %) of the new configurations, while the outliers represented respectively 2.38 % (*SD* = 0.94 %) and 1.69 % (*SD* = 0.71 %) of old and new configurations. One participant was excluded because of a number of invalid trials representing more than 10 % of the total number of trials.

Figure 7.15 displays RTs for each configuration at each block. A two-way repeated-measures ANOVA of search RTs showed significant main effects of configuration ($F(1,14) = 55.93$, $MS_e = 16645.17$, $p < .001$; Huynh-Feldt corrected degrees of freedom) and block ($F(22.34,312.75) = 10.00$, $MS_e = 8029.17$, $p < .001$, Huynh-Feldt corrected degrees of freedom). The main effect of block was accompanied by significant linear effect ($F(1,14) = 81.26$, $MS_e = 19973.26$, $p < .001$). The interaction did not reach significance ($F(20.39,285.42) = .92$, $MS_e = 7755.00$, $p > .10$). Multiple comparisons showed that RTs in old and new configurations did not differ in block 1 ($F(1,14) = 2.48$, $p > .10$), 2 ($F(1,14) = 3.32$, $p = .090$) and 4 ($F(1,14) = .05$, $p > .10$), demonstrating that the both configuration types were similarly efficiently processed at the very beginning of the experiment.

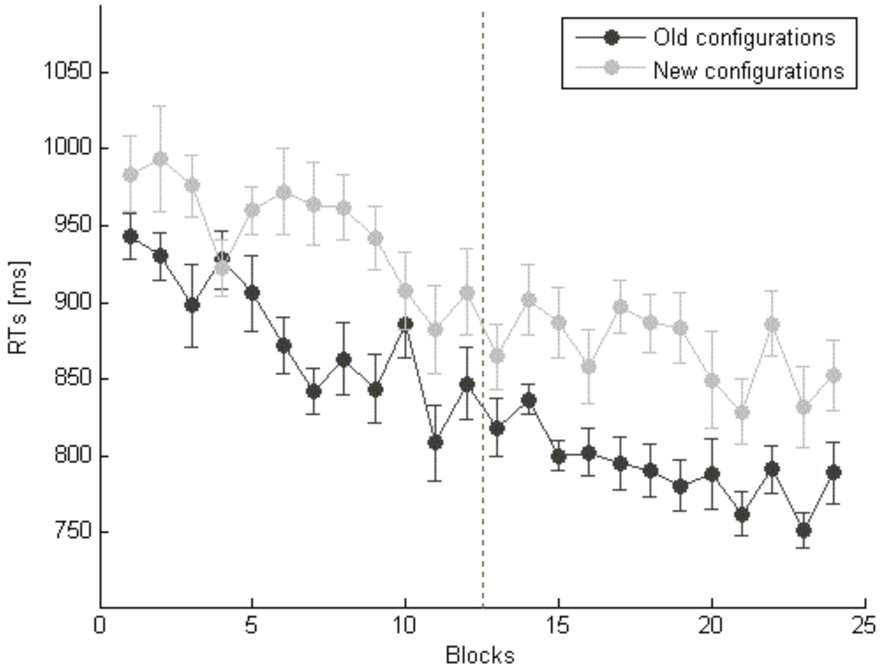

Figure 7.15 Mean RTs (and standard errors) per configuration and block in Experiment 7. The dark grey line represents RTs for old configuration trials, whereas the light grey line stands for the RTs for the new configuration trials. The dashed line represents the manipulation location.

After regrouping blocks into six epochs (see Table 7.8), a two-way (factors: configuration – epoch) repeated-measures ANOVA revealed similar results as in the block-based analysis. The main effects of configuration ($F(1,14) = 55.93$, $MS_e = 4161.30$, $p < .001$, Huynh-Feldt corrected degrees of freedom) and epoch ($F(5,70) = 27.80$, $MS_e = 3486.97$, $p < .001$) were significant, the interaction was not significant ($F(5,70) = 1.75$, $MS_e = 1506.06$, $p > .10$). Error rates for old configurations were significantly higher than for new configurations ($F(1,14) = 4.73$, $MS_e = .169$, $p < .05$), but they were not affected by epoch ($F(5,70) = 1.36$, $MS_e = .27$, $p > .10$); there was no interaction, either ($F(5,70) = .27$, $MS_e = .39$, $p > .10$).

Results of Experiment 7 show that, similarly to Experiment 6, a display containing objects of various sizes seems to accelerate the development of the contextual cueing. As reported in Table 7.8, participants responded significantly faster to targets in old than in new configurations already in the first epoch. Furthermore, changing the size of all elements in the middle of the experiment does not affect the magnitude of the contextual cueing effect. To confirm this observation, the same manipulation examinations as in previous experiments were used.

Table 7.8

Mean RTs (ms) for New and Old Configurations per epoch in Experiment 7 (standard deviations in parentheses; F value of the simple effect between old and new configurations).

	Epoch 1	**Epoch 2**	**Epoch 3**	**Epoch 4**	**Epoch 5**	**Epoch 6**
New configuration	968.97	964.64	909.93	878.00	879.24	849.88
	(96.44)	(72.94)	(84.16)	(57.87)	(85.05)	(71.36)
Old configuration	924.86	870.89	846.37	814.46	788.76	773.81
	(111.56)	(71.73)	(85.90)	(75.27)	(70.27)	(70.50)
F(1,14)	8.06	53.75	12.60	17.01	23.18	23.83
p	.013	.000	.003	.001	.000	.000

Within-experiment analyses of the size manipulation. A two-way (factors: manipulation x configuration) repeated-measures ANOVA on the whole experiment showed that both main effects of manipulation (*F*(1,14) = 62.09, MS$_e$ = 1687.83, *p* < .001; Huynh-Feldt corrected degrees of freedom) and configuration (*F*(1,14) = 55.934, MS$_e$ = 1387.10, *p* < .001, Huynh-Feldt corrected degrees of freedom) were significant. The interaction was not significant (*F*(1,14) = .60, MS$_e$ = 569.73, *p* > .10, Huynh-Feldt corrected degrees of freedom). Multiple comparisons revealed that the target was detected faster in old than in new configuration trials in the first half (old configurations: *M* = 880.70 ms, *SD* = 81.85 ms; new configurations: *M* = 947.85 ms, *SD* = 75.78 ms; *F*(1,14) = 50.19, *p* < .001), as well as in the second half of the experiment (old configurations: *M* = 792.34 ms, *SD* = 68.31 ms; new configurations: *M* = 869.04 ms, *SD* = 61.38 ms; *F*(1,14) = 34.38, *p* < .001). Although the difference between old and new configurations after the middle of the experiment (*M* = 76.70 ms, *SD* = 36.71 ms) was slightly larger than the same difference before the middle of the experiment (*M* = 67.14 ms, *SD* = 50.66 ms), they did not differ significantly (*t*(14) = -.775, *p* > .10).

Comparing the epochs just before and after the mid-experiment size manipulation for each configuration type showed slightly different results as previous analyses, namely, a significant main effect of configuration (*F*(1,14) = 24.51, MS$_e$ = 2471.08, *p* < .001), a marginally significant main effect of epoch (*F*(1,14) = 4.13, MS_e = 3703.91, *p* = .062), and a non-significant interaction (*F*(1,13) = .00, MS_e = 1713.82, *p* > .10). Although, as already mentioned, there was a significant difference between old and new configurations (*F*(1,14) = 4.72, MS_e = .16, *p* < .05), the mid-experiment change did not modify error rates of the whole experiment (manipulation: *F*(1,14) = .11, MS_e = .19, *p* > .10; interaction: *F*(1,14) = .08, MS_e = 1.09, *p* > .10, all Huynh-Feldt corrected degrees of freedom). The same analysis between epochs 3 and 4 did not show significant differences between old and new configurations (*F*(1,14) = .70, MS_e = .60, *p* > .10, Huynh-Feldt corrected degrees of freedom) or between epochs (*F*(1,13) = 4.12, MS_e = 1.11, *p* = .063, Huynh-Feldt corrected degrees of freedom). The configuration-epoch interaction was not significant (*F*(1,14) = .06, MS_e = .27, *p* > .10, Huynh-Feldt corrected degrees of freedom).

*Between-experiments analyses of the size manipulation***.** A two-way (factors: manipulation x experiment type) comparing contextual cueing effect between Experiments 1 and 7 before and after the mid-experiment size manipulation showed a significant main effect of the factor manipulation (*F*(1,29) = 5.32, MS_e = 1056.13, *p* < .05): contextual cueing was higher after the manipulation (*M* = 66.70 ms, *SD* = 47.16 ms) than before (*M* = 47.66 ms, *SD* = 53.25 ms). There was a tendency of a main effect of experiment (*F*(1,29) = 3.67, MS_e = 3666.00, *p* = .065): the global contextual cueing for Experiment 1(*M* = 42.43 ms, *SD* = 42.81 ms) was smaller than for Experiment 7 (*M* = 71.92 ms, *SD* = 42.81 ms). Although the interaction did not reach significance (*F*(1,29) = 1.32, MS_e = 1056.13, *p* > .10), multiple comparisons revealed that the contextual cueing increased significantly after the manipulation in Experiment 1 (before manipulation: *M* = 28.17 ms, *SD* = 60.25 ms, after manipulation: *M* = 56.70 ms, *SD* = 42.97 ms; *F*(1,29) = 6.16, *p* < .05), whereas the contextual cueing effect remained stable in Experiment 7 (before manipulation: *M* = 67.14 ms, *SD* = 36.71 ms, after manipulation: *M* = 76.70 ms, *SD* = 50.66 ms; *F*(1,29) = .43, *p* > .10).

The slope before the mid-experiment size manipulation in Experiment 7 was flatter (*M* = 6.27 ms, *SD* = 35.10 ms) than in Experiment 1 (*M* = 15.48 ms, *SD* = 30.33 ms), but the difference was not significant (*t*(29) = .78, *p* > .10). At a local level, the slope between epochs 3 to 4 of Experiment 7 (*M* = -.02 ms, *SD* = 82.80 ms) and Experiment 1 (*M* = 9.18 ms, *SD* = 59.34 ms) did not differ (*t*(29) = .36, *p* > .10). These results suggest that objects with various sizes accelerate the development of the contextual cueing.

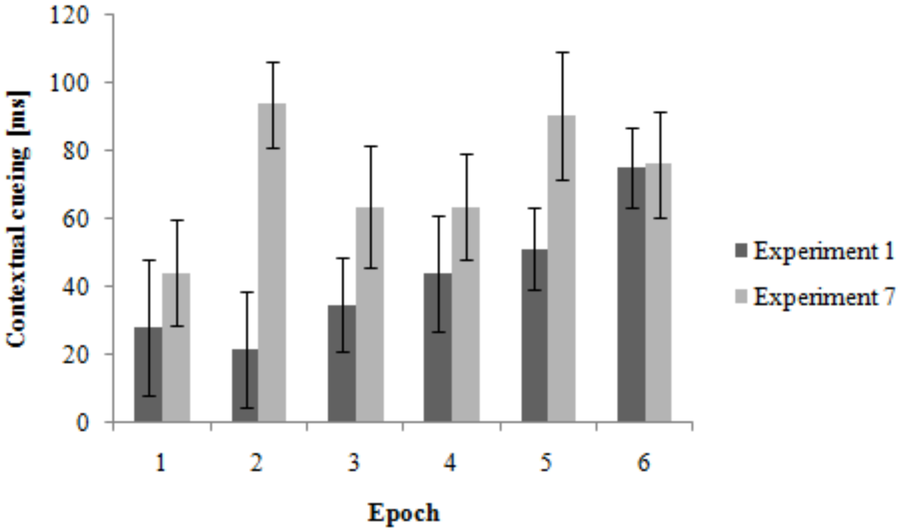

Figure 7.16. Contextual cueing effect in Experiment 1 and 7. Error bars represent standard errors.

The present analyses confirm the assumption that the size manipulation did not affect the contextual cueing effect. In addition, introducing a size difference between objects leads to a faster development of the contextual cueing effect (see Figure 7.16) compared to the standard of Experiment 1. Altogether, these results suggest that object size does modulate the contextual cueing effect in an altogether different fashion than the feature color. If size served as a direct cue for the target location, the manipulation would have abolished or, at least, reduced the contextual cueing effect (as in Experiment 2); this was clearly not observed in Experiment 7. One plausible explanation is that the size *variability* in the display generated a larger richness in the display, i.e., it increased the information content, permitting the participants to take advantage of multiple sources of information and thus to represent the relation between the distractor configuration and target location faster; such an effect is observed in studies using natural scenes as search context (Brockmole et al., 2006a, b). In this case, a size change does not affect the contextual cueing because the learning of the association between target and distractors positions is already at an optimum level before the manipulation.

7.10. Experiment 8: Size and orientation change

Similarly to Experiment 4, Experiment 8 investigated the effect of a change of size and orientation. According to results obtained in Experiment 4, a change of all features defining the distractors modifies their identity (interaction effect of changes). Changing both size and orientation should not alter the development of contextual cueing. On the other hand, Experiment 3 demonstrates that an orientation change does not interfere with the development of contextual cueing, while Experiment 7 suggests that size itself does not cue the target location, rather, the variety of information that it introduces into the display highlights the distractor configuration (additional effect of the changes). No disruption of the contextual cueing should also occur. Although each prediction is based on different observations, they predict that the contextual cueing effect should not be affected by a change of size and orientation.

7.10.1. Method

Participants. Fifteen observers (fourteen female and one male) took part in Experiment 8. All were students at the University of Fribourg. They received course credits for participation. They were aged between 19 and 32 years (median = 20 years). All observers had normal or a corrected to normal vision, including normal color vision.

Design, procedure and stimuli. The same stimuli as in Experiment 7 were used. In the middle of the experimental session, the size and the orientation of all objects changed. The size change was the same as in Experiment 7, and the orientation change was the same as in Experiment 3.

*Apparatus and setting***.** Apparatus and setting were the same as in preceding experiments.

7.10.2. Results and discussion

The same analysis procedure as in previous experiments was used. (No old configuration trials needed to be excluded because they facilitated target detection.) Error rates on average 1.02 % (*SD* = 0.91 %) for old configuration trials and 1.16 % (*SD* = 0.81 %) for new configuration trials (no significant difference: $t(14) = .84$, $p > .10$). The extremely slow responses represented 1.92 % (*SD* = 1.74 %) of old configuration trials and 3.31 % (*SD* = 2.27 %) of the new configurations, while the outliers represented respectively 2.41 % (*SD* = 0.90 %) and 1.81 % (*SD* = 0.93 %) of old and new configurations. One participant was excluded because of a number of invalid trials representing more than 10 % of the total number of trials.

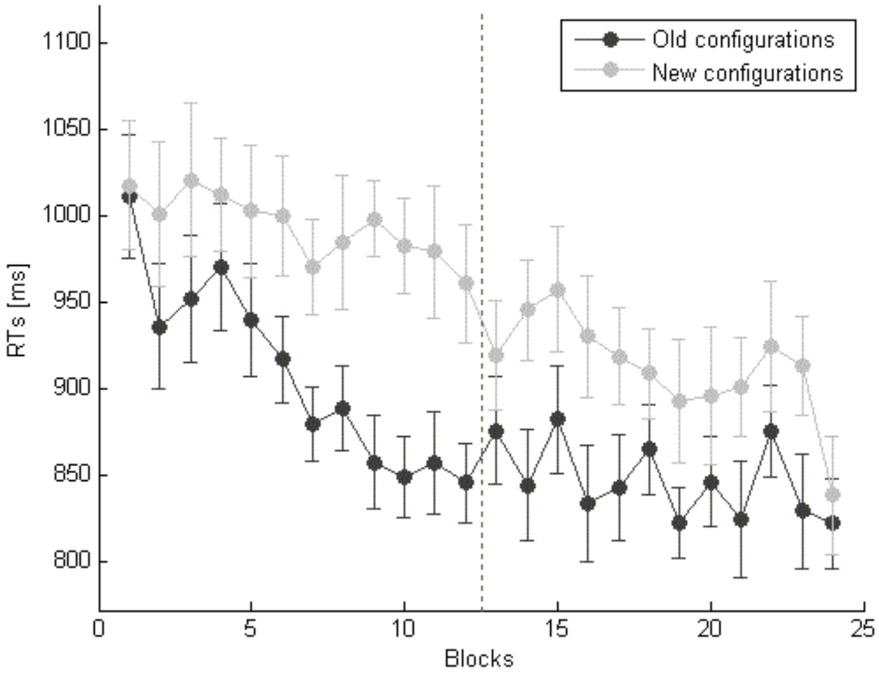

Figure 7.17. Mean RTs (and standard errors) per configuration and block in Experiment 8. The dark grey line represents RTs for old configuration trials, whereas the light grey line stands for the RTs for the new configuration trials. The dashed line represents the manipulation location.

Figure 7.17 displayed RTs for each configuration and each block of Experiment 8. As in the previous experiments, a two-way repeated-measures ANOVA on RTs revealed significant main effects of configuration ($F(1,14) = 44.74$, $MS_e = 22761.56$, $p < .001$; Huynh-Feldt corrected degrees of freedom) and block ($F(19.16,268.30) = 6.41$, $MS_e = 12315.05$, $p < .001$; Huynh-Feldt corrected degrees of freedom). The main effect of block was accompanied by significant linear ($F(1,14) = 39.09$, $MS_e = 33549.64$, $p < .001$) effect. The interaction between factors did not reach significance ($F(17.95,251.30) = 1.13$, $MS_e = 9797.40$, $p > .10$). After regrouping blocks into six epochs (see Table 7.9), a two-way (factors: configurations – epochs) repeated-measures ANOVA revealed slightly different results as in the block-based analysis. The main effects of configuration ($F(1,14) = 44.74$, $MS_e = 5690.40$, $p < .001$;

Huynh-Feldt-corrected degrees of freedom) and epoch ($F(3.25,45.56) = 17.20$, $MS_e = 5902.39$, $p < .001$; Huynh-Feldt-corrected degrees of freedom) were significant, as well as the interaction ($F(5,70) = 2.81$, $MS_e = 2308.87$, $p < .05$). Error rates did not differ in function of configuration ($F(1,14) = .71$, $MS_e = .28$, $p > .10$; Huynh-Feldt corrected degrees of freedom), or epoch ($F(5,70) = .96$, $MS_e = .56$, $p > .10$). The interaction was not significant ($F(5,70) = 1.08$, $MS_e = .39$, $p < .10$).

Experiment 8 confirms results obtained, separately, in Experiments 3 and 7, namely that a change of orientation and size does not affect the contextual cueing effect. To provide further evidence for this result, the same manipulation examinations as in previous experiments were applied.

Table 7.9

Mean RTs (ms) for new and old configurations per epoch in Experiment 8 (standard deviations in parentheses; F value of the simple effect between old and new configurations).

	Epoch 1	**Epoch 2**	**Epoch 3**	**Epoch 4**	**Epoch 5**	**Epoch 6**
New configuration	1012.52	989.35	980.05	938.00	903.99	894.39
	(120.27)	(94.39)	(83.05)	(89.44)	(97.25)	(103.48)
Old configuration	967.20	906.24	852.27	859.17	844.23	837.90
	(122.71)	(81.33)	(76.97)	(96.21)	(83.76)	(91.98)
F(1,14)	5.02	15.76	45.55	21.42	12.08	6.10
p	.042	.001	.000	.000	.003	.027

*Within-experiment analyses of orientation and size manipulation***.** Changing the size and orientation of all elements did not affect the contextual cueing effect at a global level. A two-way (factors: manipulation x configuration) repeated-measures ANOVA of the RTs of the whole experiment showed that both main effects of manipulation ($F(1,14) = 37.07$, $MS_e = 2078.15$, $p < .001$, Huynh-Feldt-corrected degrees of freedom) and configuration ($F(1,14) = 44.74$, $MS_e = 1896.80$, $p < .001$, Huynh-Feldt-corrected degrees of freedom) were significant. The interaction was not significant ($F(1,14) = 1.51$, $MS_e = 1028.56$, $p > .10$, Huynh-Feldt-corrected degrees of freedom). Multiple comparisons revealed that the target was detected faster in old than in new configuration trials in the first half (old configurations: $M = 908.57$ ms, $SD = 83.64$ ms; new configurations: $M = 993.97$ ms, $SD = 87.28$ ms; $F(1,14) = 41.49$, $p <$

.001), as well as in the second half of the experiment (old configurations: *M* = 847.10 ms, *SD* = 85.91 ms; new configurations: *M* = 912.13 ms, *SD* = 88.22 ms; *F*(1,14) = 19.74, *p* < .001). Although the difference between old and new configurations after the middle of the experiment (*M* = 65.03 ms, *SD* = 56.69 ms) was numerically smaller than the same difference before the mid-experiment orientation and size manipulation (*M* = 85.40 ms, *SD* = 51.35 ms), old and new did not differ significantly (*t*(14) = 1.23, *p* > .10).

Error rates were not affected by the manipulation. A two-way (factors: manipulation x configuration) repeated-measures ANOVA revealed no significant main effect of manipulation (*F*(1,14) = .42, MS_e = .26, *p* > .10, Huynh-Feldt corrected degrees of freedom) or of configuration (*F*(1,14) = 0, MS_e = .1.03, *p* > .10, Huynh-Feldt corrected degrees of freedom). The interaction between the factors manipulation and configuration did not reach statistical significance (*F*(1,14) = 2.57, MS_e = .51, *p* > .10).

Comparing RTs in epochs just before and after the mid-experiment orientation and size manipulation for old and new configurations revealed a different pattern of results. Although the main effect of configuration remained significant (*F*(1,14) = 60.31, MS_e = 2654.19, *p* < .001; Huynh-Feldt corrected degrees of freedom), the main effect of manipulation (*F*(1,14) = 2.55, MS_e = 1815.68, *p* < .10, Huynh-Feldt-corrected degrees of freedom) and the interaction effect were only marginally significant (*F*(1,14) = 4.07, MS_e = 2209.78, *p* = .063, Huynh-Feldt corrected degrees of freedom). The interaction reflected the fact that the difference between old and new configurations before the manipulation (*M* = 127.77 ms, *SD* = 73.32 ms) is larger than after the manipulation (*M* = 78.83 ms, *SD* = 65.97 ms; *t*(14) = 2.02, *p* = .063). Error rates were not affected by the orientation and size manipulation (configuration: *F*(1,14) = .65, MS_e = .41, *p* > .10; manipulation: *F*(1,14) = 1.07, MS_e = 1.00, *p* > .10; interaction: *F*(1,14) = 1.88, MS_e = .57, *p* > .10, all Huynh-Feldt-corrected degrees of freedom).

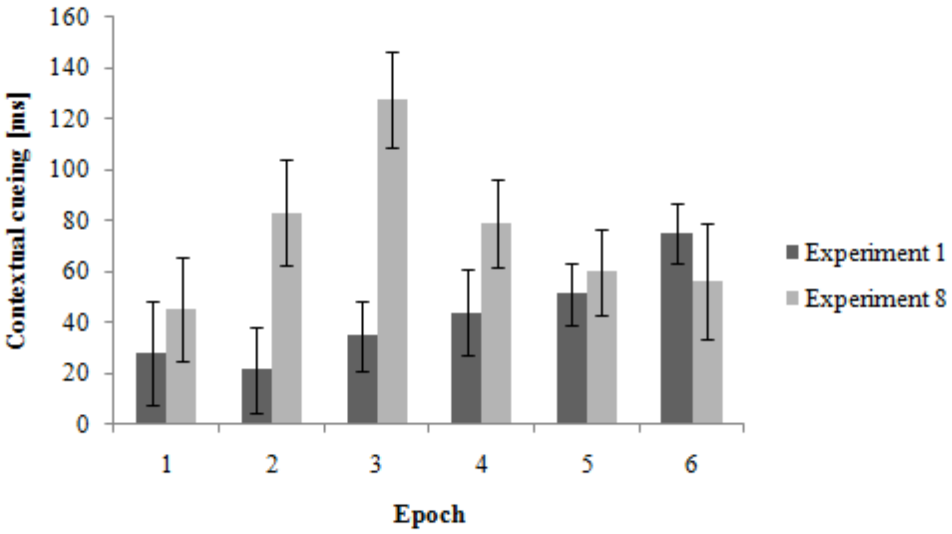

Figure 7.18. Contextual cueing effect in Experiment 1 and 8. Error bars represent standard errors.

Between-experiment analyses of the orientation and size manipulation. In contrast to previous experiments, the two-way (factors: manipulation x experiment) ANOVA comparing the contextual cueing effect at a global level showed a non-significant effect of the manipulation ($F(1,29) = .17$, $MS_e = 1499.14$, $p > .10$, Huynh-Feldt-corrected degrees of freedom), namely the increase of the contextual cueing after the manipulation was not significant (before manipulation: $M = 55.86$ ms, $SD = 62.38$ ms, after manipulation: $M = 60.72$ ms, $SD = 49.41$ ms). However, the main effect of experiment was marginally significant ($F(1,29) = 4.00$, $MS_e = 4158.13$, $p = .055$). The interaction between the factors manipulation and experiment was significant ($F(1,29) = 6.18$, $MS_e = 1499.14$, $p < .05$); multiple comparisons showed that the contextual cueing remained stable after the manipulation in Experiment 8 (before manipulation: $M = 85.40$ ms, $SD = 51.35$ ms, after manipulation: $M = 65.03$ ms, $SD = 56.70$ ms; $F(1,29) = 2.08$, $p > .10$), while, as already described in previous experiment, the contextual cueing effect increased significantly after the manipulation in Experiment 1 (before manipulation: $M = 28.17$ ms, $SD = 60.25$ ms, after manipulation: $M = 56.70$ ms, $SD = 42.97$ ms; $F(1,29) = 4.34$, $p > .10$).

Analyzing the slopes of the contextual cueing after the manipulation showed a tendency of a difference between Experiments 1 and 8 ($t(29) = 2.034$, $p = .051$, the slope in Experiment 1 was positive ($M = 15.48$ ms, $SD = 30.33$ ms), indicating a progression of the contextual cueing effect, whereas the slope in Experiment 8 was negative ($M = -11.17$ ms, $SD = 42.06$

ms), reflecting a decrease in the effect. Finally, at a local level, the behavior of the slope between epochs 3 to 4 differed in tendency between experiments (*t*(23.36) = 2.043, *p* = .052). In Experiment 1, the slope was slightly positive (*M* = 9.18 ms, *SD* = 59.34 ms), whereas the slope in Experiment 8 was strongly negative (*M* = -48.94 ms, *SD* = 94.02 ms), suggesting at first glance that the manipulation reduced the contextual cueing effect.

One alternative explanation is that using objects of different sizes makes displays more distinguishable than variations caused by other features, leading to a faster categorization between old and new configurations; this is observed with natural scenes (e.g., Brockmole et al., 2006a, b). Consequently, size differences generate a larger contextual cueing effect right in the beginning of the experimental session. However, in the course of the experiment, participants may reach a minimal detection RT threshold for old configurations (as in Experiment 3), leading the detection time for old configurations to stagnate around 850 ms (see Figure 7.17). Simultaneously, the detection times for new configurations carry their monotone decrease over the manipulation, coming closer to the detection times for old configurations, thus reducing the contextual cueing effect and generating a negative slope after the manipulation.

Together, Experiments 7 and 8 demonstrate that introducing a size difference between displayed objects generates a faster contextual cueing development. In addition, the size manipulation does not seem to modulate the contextual cueing effect. This suggests that size itself does not cue the target location. Rather, as already argued in Experiment 7, the results of Experiment 8 suggest than the size *variability* in the display accentuates the informational richness of the display, leading to a faster learning of the association between target and distractor positions.

7.11. General discussion

As previously demonstrated, the relation between distractor features, as motion or color, and the target position can efficiently be learned (see Chun & Jiang, 1999; Endo & Takeda, 2002, 2004; Huang, 2006). This study was aimed at confirming and extending the specific contribution of distractor-defining features, as color, orientation and size, in the contextual cueing effect. To investigate this issue, one or two feature(s) of the distractors changed in the middle of the experiment.

Results demonstrated that color was the single feature to affect the contextual cueing effect. Indeed, a simultaneous change of color hue and luminance stopped the contextual cueing progression (Experiment 2), confirming the role of this feature in the elaboration of the contextual cueing observed in previous studies (Endo & Takeda, 2002, 2004; Huang, 2006). To distinguish which color aspect generates this effect, two follow-up experiments examine the impact of either a change in hue (Experiment 5) or luminance (Experiment 6). In both cases, the contextual cueing was not altered. This lack of contextual cueing effect found in Experiment 2 might consequently result from an interaction between both color aspects. Therefore, this observation suggests that the contextual cueing alteration observed in Huang's study stems from a change of both color aspects.

However, Experiments 5 and 6 do not present the same pattern in the contextual cueing development. The pattern observed in Experiment 5 is similar to the one of the replication, whereas, in Experiment 6, the contextual cueing effect increases faster than in the replication, suggesting that, in contrary to hue, luminance improves substantially the richness of the display. This observation can be easily demonstrated by removing either luminance or hue from a color picture depicting a natural scene. Removing hues let picture details intact, whereas, when luminance is removed, objects are poorly defined and the scene structure is difficult to recognize (see for instance Lennie, 2000).

However, a change in orientation or size of the distractors (respectively Experiment 3 and 7) does not modulate the contextual cueing effect. One reasonable explanation for the lack of contextual cueing modulation in Experiment 3 can stem from the functional aspect of orientation in the task. Indeed, orientation determines search difficulty. If all Ls were upright, the target would pop out directly from the display. In such a case, learning the context would not be helpful anymore to solve the task (e.g., Wolfe & Horowitz, 2004). Because of its tied link to the task, distractor orientation does not seem to serve as valuable predictive cue of the target location.

Although not directly implicated in the task, as orientation is, Experiments 7 and 8 report that a change of distractor size does not disturb the development of the contextual cueing effect. Nevertheless, as in Experiment 6, introducing size variability between displayed objects might have enhanced the display richness. Increasing the display richness might highlight the distractor positions, and expedited the development of the contextual cueing effect. Studies using natural scenes that display usually a larger richness for the stimuli than artificial displays found similarly a faster development of the contextual cueing effect (Brockmole et al., 2006a, b). In such a case, the minimal time required to solve the task is earlier reached, and RTs for old configuration trials remain stable earlier than in the replication. However, while staying constant for old configuration trials, RTs for new configuration trials continue to decrease, reducing consequently the size of the contextual cueing effect, leading thus to a reduced of the contextual cueing throughout the experimental session.

Finally, Experiments 4 and 8 revealed that changing the two features constituting the distractors, respectively color and orientation, and size and orientation, does not ruin the contextual cueing effect. Although not modifying the general shape of the distractors, the general change seems to act as an identity change. Indeed, Chun and Jiang (1998) already observed that a change of the distractor shape, leading consequently to a modification of the distractor identity, does not disturb the contextual cueing effect.

To sum up, tested visual features, namely orientation, size and color, do not contribute in a similar fashion to the development of the contextual cueing. Orientation, because being an integral part of the search task, cannot provide a reliable cue of the target position. On the other hand, size seems to enhance the display richness and to allow a faster development of the contextual cueing. The fact that a change of this feature does not cancel out the learning process suggests that size does not serve as a direct cue for the target position, but seems rather to facilitate the representation of the relation between target and distractor locations by increasing the display richness. Finally, color was the unique feature that was able to abolish the contextual cueing. However, this effect seems to be due to an interaction between chromatic and achromatic aspects of color. Further research is required to investigate the exact nature of the mechanism responsible for the contextual cueing progression stopping caused by a change of both color characteristics.

8. Synopsis

Experiments presented in the preceding chapters were aimed at a better understanding of the temporal and spatial mechanisms of featural signals integration under search circumstances, within and between sensory modalities. Another topic of interest was the influence of practice in visual feature integration during a search task. Finally, the relative contribution of visual features in learning the association between spatial and featural characteristics of the search display, labeled as contextual cueing effect, was examined.

The methodology privileged to address the first issues was the detection of redundantly defined targets, whose processing has been deeply investigated. The boost of RTs (RTs) observed for this type of targets (compared to singly defined targets), termed redundancy gains, have been explained by two different classes of models. Although they both assume that feature signals are processed independently and in parallel, they diverge concerning the mechanisms that generate the response. One of them postulates that redundancy gains are due to “statistical facilitation” arising as a result of a parallel race of independent signals to trigger a response (Race Model; Raab, 1962). The second account assumes that independent feature signals feed into a common module that triggers the response. In contrast to a parallel race, both signals contribute to the activation of the response, thus the term parallel “co-active” model (e.g., Miller, 1982). Miller proposed a method for differentiating parallel race and parallel co-active models, labeled Race Model Inequality (RMI; Miller, 1982, 1986). He proved that all models postulating a strict parallel processing between features, as the Race Model (Raab, 1962), do not violate this inequality. Violations of this inequality speak consequently in favor of a feature parallel co-active processing.

8.1. Similar feature processing architecture within and cross modality

Cognitive models investigating feature integration, as Guided Search (e.g., Wolfe, 1994), were first designed to explain the mechanism underlying the orienting of attention during feature detection and conjunction tasks. For this reason, they strove to explain the spatial properties of unimodal feature integration, but, due to the task conception, neglected somewhat its temporal aspects. Indeed, in the traditional procedure of feature detection and conjunction tasks, all items are displayed simultaneously, making difficult, or even impossible, to gauge the respective temporal contribution of features characterizing the target.

Inspired from Schönwälder's (2006) change paradigm that takes account of this aspect, two tasks involving redundantly defined targets were reported in Chapter 3. In each task, the target identity was unveiled after feature changes of a single item; these feature changes were separated by a variable time interval. This asynchrony between feature changes permits to evaluate the respective contribution of both features constituting the target. Three different features, namely color, orientation and local motion (i.e., all items in the display move horizontally within a small space range in a consistent fashion), were paired in three different combinations. In the first task, participants were asked to react to any change in the search display (change detection task), whereas, in the second task, participants were instructed to react only to specific predefined feature combinations (change conjunction task).

This change paradigm revealed that visual feature signals do no present the same processing latency. The feature change detection paradigm demonstrated that color has to change about 20 ms after orientation and local motion to be integrated at best, whereas orientation and local motion are optimally integrated when both features change simultaneously. This suggests consequently that, in a change detection task, color is processed faster than the two other features. Furthermore, the fact that RMI violations (Miller, 1986) could be observed in each feature combination, but not necessary when features change simultaneously, contradicts recent studies on detection of redundantly defined targets (e.g., Poom, 2009) demonstrating that some feature combinations, as for instance motion and color, are not processed according to a parallel co-active model.

These observations question also the actual form of the saliency maps summation model (e.g., Cave & Wolfe, 1990; Koch & Ulmann, 1985; Wolfe, 1994). This type of models assumes that features are extracted in parallel and reported onto independent feature-specific maps that compute the saliency signal for all items in the display. These feature-specific saliency maps are then summed onto an overall saliency map that serves to orient attention toward the most salient depicted item. Furthermore, it postulates implicitly that the processing of visual features starts simultaneously. If assumed that the saliency signal development in feature-specific saliency maps (correlated to the feature processing) is constantly reported onto the master map according to a parallel co-active processing (e.g., Miller, 1982), two features having the same processing speed will generate approximately a comparable amount of saliency signal at each time of their processing. However, if both features have different processing speed, the respective contribution of each feature to the common saliency signal becomes asymmetric. In this case, the amount of saliency signal necessary to trigger the target detection is reached later than with features having synchronous processing speed. Although more rapidly detected that singly defined targets, redundantly defined targets with asynchronous processing speed do not reach the detection threshold early enough to generate significant RMI violations, as observed in studies presenting all items simultaneously (e.g., Poom, 2009). Postponing the processing of the fastest featural signal would allow counterbalancing the asymmetric contribution of asynchronous processed features to the common saliency signal at the master map level. In the change paradigm, RMI violations would be consequently observed when features do change asynchronously, as observed in Experiment 1 of Chapter 3.

On the other hand, when the task required a deeper processing of feature signals, as the identification of a feature combination (Experiment 2), participants took more time to respond to the same redundantly defined targets than in the detection task. Furthermore, the longest RTs were systematically observed when features changed simultaneously and they diminished as a function of the time interval between feature changes.

Nevertheless, these results do not contradict the hypothesis of an asynchronous processing speed between feature signals. The fact that RTs are slower in change conjunction task suggests that feature identification requires more cognitive resources than a feature detection. However, these resources seem to be limited. When many features have to be identified simultaneously, the cognitive resources do not suffice to process them at the same speed than when a unique feature has to be identified. This feature processing overlap leads to a general slowdown of the processing system. Simultaneous feature changes generate a maximal processing overlap, whereas a time interval between feature changes reduces this overlap, permitting to the feature that changes first to be already (partially) processed before the second feature change. Consequently, RTs diminish as a function of the size of the time interval between feature changes.

According to this reasoning, the processing overlap is always maximal when features change simultaneously, regardless of the relative feature processing speed. However, this latter influences the RTs decrease related to the size of the time interval between changes. When both features presented the same processing speed, the overlap zone decrease is similar whatever the feature that changes first. Due to this particularity, RTs diminish in a symmetrical fashion as a function of the time interval separating feature changes. On the other hand, in the case of an asynchronous processing speed, the RT pattern is different. When the fastest processed feature changed first, feature processing overlap diminishes faster (compared to a first change of the slowest feature), causing consequently a steeper response time reduction associated with the size of the time interval between changes. This hypothesis found support in the comparison of (linear) slopes for each feature that changed first within each paradigm. Results showed that local motion seems to be processed faster the color, orientation faster than local motion, whereas color and orientation seem to be processed at the same speed.

Findings in Chapter 3 suggest thus that visual feature signals are not processed at the same speed. Furthermore, the relative processing speed depends on the task requirements. In feature change detection tasks, color seems to be faster processed than orientation and motion, whereas, the feature change conjunction tasks present a different, less clear pattern. These observations are consistent with other recent studies demonstrating the dependence of the processing speed to the task requirements (Adams & Mamassian, 2004; Bedell et al., 2003; Clifford, Arnold & Pearson, 2003).

In Chapter 4, the integration of multisensory features was addressed with a similar methodology as in Chapter 3. In Experiment 1, a tone and an array of visual stimuli were presented, and participants were instructed to react to any change in the display. In single change trial, either the tone frequency or the color of a single visual item changed, whereas, in a redundant change, both tone frequency and the color of an item changed simultaneously. Results showed that redundant changes were significantly faster detected than single changes, producing redundancy gains and RMI violations (Miller, 1982), confirming the parallel co-active processing of multimodal signals (e.g., Diederich & Colonius, 2004; Gondan et al., 2005; Miller, 1982, 1986).

Experiment 2 uses the complete procedure of the feature change detection paradigm (namely time interval between feature changes), and demonstrated that, more RMI violations were observed when color changed simultaneously or 20 to 40ms before sound. These results are coherent with behavioral (e.g., Diederich & Colonius, 2004) and neurophysiologic studies (e.g., Molholm et al., 2006).

Taken together, results of Chapters 3 and 4 lead to two main assumptions. First, feature integration seems to be sensitive to the feature processing speed. Cognitive models investigating or based on feature integration should thus take this feature characteristic into account (as an adapted version of the Guided Search model outlined in Chapter 3). Second, these findings provide additional evidence in favor of a supramodal feature processing (e.g., Wright & Ward, 2008) under feature detection task requirements (as developed in Chapter 2). Because both uni- and multimodal paradigms using the same methodology provide results pointing into the same direction, it could be assumed that a single mechanism is responsible for the processing of both uni- and multimodal features. Moreover, this mechanism could be based on a supramodal overall saliency map, in which saliency signals from features of the different modalities would be integrated (a similar concept is proposed by Wright & Ward, 2008) to guide attention toward the most salient object. However, such a supramodal saliency map implicates that the external space is represented regardless of the feature-specific spatial coordinates (namely, eye-centered for vision, head-centered for audition, and body-centered for touch). This assumption finds support in recent research, demonstrating that most of the neurons from a substructure of the posterior parietal cortex, the ventral intraparietal area, respond to visual and auditory stimuli having a same spatial origin (Schlack, Sterbing-D'Angelo, Hartung, Hoffmann & Bremmer, 2005). Moreover, reaching behavior toward visual, auditory, proprioceptive or imaginary targets seems to use a same, eye-centered, representation of the external space (Pouget, Ducom, Torri & Bavelier, 2002). According to these studies, the existence of a supramodal saliency map based on standardized spatial coordinates is not unconceivable.

8.2. Orientation of the attentional and ocular foci monitored by a similar mechanism

Experiments reported in Chapter 5 were aimed at investigating the control of the oculomotor system. As already proposed for attention, for example in Guided Search model (Wolfe, 1994), one plausible mechanism monitoring eye movements can be based on a spatial saliency signal. According to this model, the relative saliency of an object depends on its contrast with its neighbors: the more difference there is between the target and distractors objects, the more chance the target has to be sampled first. This hypothesis is confirmed by feature detection tasks involving redundantly defined targets (as in Chapter 3). If eye movements are based on a similar spatial saliency-based signal, a redundantly defined target, due to its larger spatial saliency signal, should elicit a saccade faster than a singly defined target.

Results of the feature detection task in Experiment 1 give support to this hypothesis by showing that, if any eye movements are made during the display onset, redundantly defined targets presented shorter saccade latencies than singly defined targets. Furthermore, redundancy gains and RMI violations (Miller, 1982) were observed for saccade latencies, providing evidence that both features contributed to the saliency signal responsible for the triggering of the saccade.

This finding was confirmed by Experiment 2 demonstrating that the overall saliency signal arises effectively from the spatial summation of saliency signals generated by both dimensions defining the target. When both features were physically separated (two distinct items wearing each one of the features), saccade latencies generated neither redundancy gains, nor RMI violations.

Finally, experiments of Chapter 5 demonstrated that the use of eye movements depends on the task requirements; detecting a redundantly defined target (feature detection task of Experiment 1) required in average less eye movements than identifying the feature combination characterizing the target (feature conjunction task of Experiment 1, similar to feature change conjunction task presented in Chapter 3). Furthermore, comparing oculomotor parameters between both tasks revealed that saccade latencies were even shorter in the feature conjunction than in feature detection task. These findings demonstrate consequently that the saliency-based control of the oculomotor system can be modulated according to the task (namely identifying the feature combination defining the target), and suggest that this mechanism can be envisaged as the “default” control mode of eye movements. This last assumption is corroborated by studies observing longer latencies for intentionally, top-down controlled saccades (e.g., Hallett, 1978; Shepard et al., 1986; Van Zoest et al., 2004).

Although these results provide strong evidence that eye movements are guided, as attention seems to be, by a spatial saliency signal, this does not necessary implicate that both attentional and oculomotor systems are as one. Indeed, it has been demonstrated that attentional and ocular foci can move independently (e.g., Posner, 1980; Posner et al., 1978, 1980). The present findings suggest rather that attentional and oculomotor systems are interdependent (Wright & Ward, 2008), sharing common mechanisms, as spatial saliency guidance, and resources, as brain structures (e.g., Beauchamp et al., 2001; Corbetta et al., 1998; Nobre et al., 2000), at some points in the feature processing.

Due to its spatial organization of inputs and outputs as well as its activation during ocular and attentional shifts, one plausible neural correlate of the oculomotor saliency map could be found in the colliculus superior. The superficial layers of this midbrain structure receive direct input from retinal ganglion cells and from the primary visual cortex organized in visuospatial maps (Lund, 1972). Receptive fields of its neurons are sensitive to motion contrasts (Davidson & Bender, 1991), making him a good candidate in orienting eye movements and exogenous attention. Neurons of the colliculus superior are also activated in the execution of eye movements (Kustov & Robinson, 1996; Wurtz & Goldberg, 1972) and in shifts of attention (Goldberg & Wurtz, 1972; Kustov & Robinson, 1996), while a direct electrical stimulation of the neurons in its deep layers elicits saccades (e.g., Schiller & Stryker, 1972). Moreover, their receptive fields are topologically arranged in an oculomotor map coding the size and direction of the electrically generated saccades (Robinson, 1972). Additionally, this structure was explicitly pointed out as a possible location of the visual saliency map (Corballis, 1998; McPeek & Keller, 2002; Reuter-Lorenz, Nozawa, Gazzaniga & Hughes, 1995).

8.3. Practice can modulate feature processing

Chapter 6 from this present work was aimed at investigating whether practice can modify the way features are processed in a visual feature detection task involving redundantly defined targets, as it can improve discrimination of visual objects or characteristics (e.g., Fahle, 2004; Lu et al., 2005; McKee & Westheimer, 1978; Schoups et al., 1995). To address this issue, a feature detection task involving targets defined by color and orientation was repeated in four sessions in the course of the same week.

Results indicated that practice improved significantly the detection of any target from the first to the second session and remained constant till the last session. Furthermore, redundancy gains were not affected by practice, whereas RMI violations, attestation of a parallel co-active processing, were observed in the third session. This result suggests thus that feature processing is not fixed and can be modified by practice. Consequently, evidence of a parallel co-active processing is easier to observe in experienced participants.

Nevertheless, being able to demonstrate that a parallel co-active model seems to govern feature processing suggests that the perceptual system uses this mechanism under normal circumstances. The fact that RMI violations occurred only in third session can be attributed to the artificial experimental settings. Because giving a symbolic manual response to a simplified representation of a visual scene has little correspondence in everyday life, naïve participants need some familiarity with the task so that their responses reflect a parallel co-active processing.

8.4. Features as a cue for implicit memory

Observations from preceding chapters suggest thus that feature signals, regardless of their sensory origin, are processed according a parallel co-active mechanism that integrates their spatial and temporal properties. Furthermore, finding evidence for this processing can need some habituation to the task to be revealed. However, in daily life, the context, in which an object is to be searched, is seldom as homogeneous as in experiments of preceding chapters and the visual scene is therefore richer in details, making the target object more difficult to spot. Nevertheless, if the situation is repeated, context richness could serve as cue to find this target object. On the other hand, if this repeated context changes, finding the target object becomes harder. For instance, if all the products in your bathroom cabinet are mixed up, finding your hairspray or your razor would take more time than when they are at their usual place.

Chapter 7 focuses the role of visual features in learning the association between spatial and featural characteristics of the search display. It has been demonstrated that repeating the context in which a target appears improves performances in a visual search task (e.g., Chun & Jiang, 1998). Although this effect, labeled as contextual cueing, was attributed exclusively to a repetition-based memory of the spatial configuration of objects in the display, recent studies demonstrated that objects features, as color, can also cue the target location (e.g., Huang, 2006).

In order to examine the relative contribution of different features in contextual cueing, eight experiments were designed. The first one was a replication of the seminal experiment of Chun and Jiang (1998) and served as baseline for the following experiments. Participants' task consisted to find a target surrounded by distractors with various orientations (a T among Ls) and to indicate which side (left or right) the target was tilted to. Furthermore, half of the displays that were presented in the first block were repeated throughout the whole experiment, whereas the other half of trials was newly generated at each block. Contextual cueing refers to the benefit in RTs for repeated trials, in comparison to non-repeated trials. As expected, the first experiment replicated Chung and Jiang (1998)'s results, demonstrating a constant growth of the contextual cueing. The seven following experiments use the same paradigm, but implicate a change of one or two object features in the middle of the experimental session. If a feature can efficiently cue the target location, a change of this feature should consequently prevent the development of this effect, as demonstrated by Huang (2006) for color.

Results demonstrated that features do not have the same contribution in the contextual cueing development. Color was the only feature whose change prevents the development of the contextual cueing. However, when only luminance or hue changed, the contextual cueing was not affected, suggesting that the effect observed with a color change resulted from the interaction of color aspects.

Changing the orientation of the distractors does not alter the contextual cueing. This seems to be due to the particular role of this feature in the search display. Distractors orientation heterogeneity is the source of search difficulty. If all distractors shared the same orientation, the target would be more easily detected (e.g., Wolfe & Horowitz, 2004) and learning context characteristics would be superfluous. Due to this tied link with search efficiency, distractors orientation could not serve as effective cue for the target location.

Although not tied implicated in the task, as orientation does, size does not directly serve as a cue for the target position. Changing the objects size does not alter the development of the contextual cueing. However, size, as luminance, has a particular effect. Compared to the baseline experiment, experiments involving objects with different size or luminance, present a faster development of the contextual cueing that tends to diminish also rapidly. Instead of a linear progression, as observed in the baseline, contextual cueing takes a parabola-like shape. A close look at the results showed that RTs for repeated and non-repeated trials do not present similar pattern in their progression. RTs for the repeated trials decreased steeper than in the replication and stabilized relatively early in the experiment, suggesting that participants reached an optimal RT for the task. However, RTs for non-repeated trials diminished more gradually. Consequently, the gap between both curves increases rapidly at the beginning of the experiment, and is subsequently reduced, producing this parabola-like curve. According to these findings, instead of directly cueing the target position as color, size and luminance seem to enhance the display richness and to enlighten distractors configuration. Because the relation between target and distractors locations is fast learned, a change of these features does not affect the contextual cueing.

Finally, a change of both features defining the target, especially for color and orientation, does not affect the contextual cueing. These observations are similar to results obtained by Chun and Jiang (1998, Experiment 2) demonstrating that change of the distractors identity in the middle of the experiment does not alter the contextual cueing, and suggest therefore that a complete feature change is equivalent to changing distractors identity. Due to the lack of reliability of all object features, participants rely only on spatial configuration of the distractors to find the target.

Results obtained in Chapter 7 demonstrate thus that tested feature signals contribute differently to the contextual cueing. Orientation, due to its tied implication in the task, cannot cue the target location, while size and luminance create more variety in the display, what seems to enlighten objects spatial configuration. Color is the only feature that can alter the contextual cueing, confirming that this feature can efficiently cue the target location (e.g., Huang, 2006). Surprisingly, a change of both hue and luminance is necessary to cause this effect, suggesting that participants encode both color aspects during the learning phase.

9. Summary in French

Les expériences exposées dans le présent travail visent à une meilleure compréhension des mécanismes temporels et spatiaux de l'intégration des caractéristiques dans des conditions de recherche, tant à l'intérieur d'une même modalité qu'entre les différentes modalités sensorielles. Un autre thème est l'influence de la pratique sur l'intégration des caractéristiques visuelles. Finalement, une série d'expériences ont investigué la contribution respective des caractéristiques visuelles dans l'apprentissage de la relation entre les caractéristiques des objets et leur configuration spatiale dans une scène de recherche.

La recherche, et tout particulièrement la recherche visuelle, fait partie intégrante de la vie quotidienne, comme chercher ses clés ou son téléphone portable sur son bureau. En règle générale, ces objets sont rapidement découverts car, la plupart du temps, ils diffèrent de façon claire des autres objets qui les entourent car ils sautent littéralement aux yeux (*pop out* en anglais). Un stylo rouge est facilement détectable au milieu d'un plumier contenant des stylos bleus, alors que la Tour de Pise se distingue des bâtiments avoisinants entre autres par son orientation particulière et un animal tapi dans la jungle devient visible lors qu'il se met à bouger. Un objet présentant une caractéristique particulière, comme une couleur, une orientation ou un mouvement qui lui est propre, est donc facilement détecté parmi d'autres objets présentant une certaine homogénéité (p. ex., Treisman, 1988).

Cependant, lorsque les objets entourant l'objet-cible deviennent plus hétérogènes, la recherche devient plus difficile. Treisman et collaborateurs (p. ex., Treisman & Gelade, 1980) ont observé qu'un objet-cible se trouvant parmi d'autres objets homogènes (p. ex., une barre rouge et horizontal au milieu de barres vertes et verticales) saute toujours aux yeux, indépendamment du nombre de d'objets distracteurs l'accompagnant. Plus formellement, lorsque la cible diffère des distracteurs par une caractéristique lui étant propre, ce type de recherche visuelle prend le nom de tâche de détection de caractéristiques (*feature detection task*). Néanmoins, lorsque la cible se trouve parmi des distracteurs hétérogènes partageant des caractéristiques avec l'objet-cible (p. ex., la même barre rouge et horizontale au milieu de barres rouges et verticales et de barres vertes et horizontale), son temps de détection augmente en fonction du nombre de distracteurs qui l'entourent. Parce que la cible est définie par une combinaison unique de caractéristiques, ce type de recherche a été appelé recherche de conjonction de caractéristiques (*feature conjunction task*).

Ce qui distingue les deux tâches est la saillance (ou contraste) relative de la cible par rapport aux distracteurs. Une cible peut être plus facilement détectée au milieu des distracteurs homogènes d'une tâche de détection de caractéristiques que parmi les distracteurs hétérogènes d'une tâche de conjonction car le contraste (ou saillance) entre la cible et les distracteurs est plus important dans la première tâche que dans la seconde. En se basant sur ces observations, Wolfe (1994) proposa un modèle, appelé Recherche Guidée (*Guided Search*), dans lequel l'attention est guidée par la saillance de la scène visuelle. Chaque caractéristique, comme la couleur, l'orientation, le mouvement, ou la taille, est traitée par des détecteurs arrangés de façon topographique qui analysent la différence locale entre les valeurs de chaque caractéristique sur l'ensemble de la scène visuelle et génèrent des signaux locaux de saillance qui forment ensemble une « carte » représentant les différents niveaux de saillance de la scène visuelle pour chaque caractéristique (*saliency map*). Ces différentes cartes de saillance spécifiques sont par la suite sommées sur une carte de saillance générale (*overall saliency map*). A ce niveau, la scène visuelle n'est plus représentée qu'en termes d'intensité des signaux de saillance, comme les courbes de niveau d'une carte topographique. Finalement, l'attention est guidée vers le plus haut pic de saillance sur la carte de saillance générale. Dans une tâche de détection de caractéristiques, la cible est l'élément le plus saillant car elle présente une caractéristique qui lui est propre. En revanche, dans une tâche de conjonction de caractéristiques où cible et distracteur partagent certaines caractéristiques, le pic de saillance générée par la cible est masqué parmi les pics de saillance des distracteurs, rendant cette dernière moins visible que dans une tâche de détection de caractéristiques et obligeant l'observateur à scanner l'écran (*display*) pour la trouver.

La saillance de la cible module donc l'efficacité de la recherche. Une cible qui est relativement moins saillante qu'une autre, par exemple dans une tâche de conjonction, résulte en une recherche moins efficace. Alors que nous accomplissons la plupart du temps des tâches de type conjonctive, il existe des situations, réelles ou artificielles, dans lesquelles les objets-cibles sont sur-définis par rapport à leur contexte, comme par exemple les panneaux de signalisation qui sont conçus pour être très facilement repérés au milieu de leur environnement. Dans une recherche visuelle, de telles conditions sont atteintes par l'implication de cibles définies de façon redondante qui diffèrent des distracteurs par plus d'une caractéristique, comme une barre rouge et horizontale parmi des barres vertes et verticales. Mais comment sont traitées les multiples caractéristiques d'une cible redondante ?

L’analyse des temps de réaction permet de distinguer trois mécanismes de traitement des caractéristiques potentiels. Malgré une architecture différente, chaque modèle suppose que chaque caractéristique est traitée par un module spécifique. Le premier modèle, appelé traitement sériel (p. ex., Grossberg, Mingolla & Ross, 1994), suggère que ces modules de traitement spécifique à chaque caractéristique sont montés les un derrière les autres, comme les perles d’un collier. Ce type d’organisation implique que la cible ne peut être détectée qu’après le traitement de la dernière caractéristique. Cependant, ce modèle de traitement ne peut pas expliquer les résultats d’études récentes conduites par Krummenacher et collègues (Krummenacher et al., 2001, 2002a; Töllner et al., sous presse; Zehetleitner et al., 2009). En effet, ces derniers ont démontré qu’une cible redondante se différenciant des distracteurs par deux caractéristiques est plus rapidement détectée qu’une cible ne se distinguant des distracteurs que par une seule caractéristique. Cette diminution des temps de réaction pour les cibles définies de façon redondante a été désignée sous le terme de gains de redondance (*redundancy gains*).

Deux modèles ont été proposés pour expliquer cette réaction accélérée pour les cibles définies de façon redondante. Le premier d’entre eux suppose que les gains de redondance sont dûs à une facilitation statistique résultant d’une course entre des caractéristiques traitées de façon indépendante pour déclencher une réponse reflétant la détection de la cible (modèle de la course, ou *race model*; Raab, 1962). Le second modèle postule quant à lui que les signaux indépendants alimentent un module commun qui déclenche la réponse. Contrairement au modèle de la course, les deux signaux contribuent à l’activation de la réponse, d’où le terme de modèle de traitement « parallèle coactif » (Miller, 1982). Bien que les deux modèles supposent que les signaux des caractéristiques sont traités de façon indépendante et en parallèle, ils divergent sur les mécanismes déclenchant la réponse. Le modèle de la course parallèle suppose que la réponse indiquant la présence de la cible est déclenchée lorsque l’un des signaux dépasse un seuil requis pour déclencher la réponse. Partant du principe que les distributions des temps de réaction pour les signaux caractérisant les cibles définies par une seule caractéristique se chevauchent et que chaque signal peut gagner la course dans certains essais, les temps de réaction pour les cibles redondantes sont *en moyenne* plus rapides qu’attendu sur la base des distributions des temps de réaction pour les cibles définies par une seule caractéristique.

Miller (1982) suggère quant à lui que la réponse est générée à partir de la sommation de l’activation de traitement des deux signaux. Lorsque cette accumulation d’activation excède une certaine quantité, la réponse est déclenchée. Miller (1982, 1986) proposa une procédure permettant de différencier le modèle de traitement parallèle co-actif du modèle de la course, appelée inégalité du modèle de la course (R*ace Model Inequality*, ou RMI). Il prouva que tous les modèles postulant un traitement strictement parallèle des caractéristiques, comme le modèle de la course (Raab, 1962), ne peuvent pas violer cette inégalité. Une violation de cette inégalité témoigne donc d'un modèle de traitement parallèle coactif. Utilisant cette procédure, Krummenacher et al. (p. ex., Krummenacher et al., 2001, 2002a, b) démontrèrent que les gains de redondance pour les caractéristiques visuelles sont générés selon un modèle de traitement parallèle coactif, c'est à dire que l'activation cumulée des deux caractéristiques est responsable du déclenchement de la réponse. En d'autres termes, la détection de la cible semble provenir de l'intégration des différentes caractéristiques visuelles.

9.1. Un traitement similaire pour les caractéristiques sensorielles intra et intermodales

Comme mentionné plus haut, les modèles cognitifs investiguant l'intégration des caractéristiques, comme la Recherche Guidée (Wolfe, 1994), furent conçus en premier lieu pour expliquer le mécanisme sous-tendant l'orientation de l'attention durant les tâches de détection et de conjonction de caractéristiques. Pour cette raison, ils se sont efforcés d'expliquer les propriétés spatiales de l'intégration des caractéristiques, mais, à cause de la conception des tâches, ont quelque peu négligé ses aspects temporels. En effet, dans la procédure traditionnelle des tâches de détection et de conjonction, tous les éléments sont présentés simultanément à l'écran, rendant difficile, voire impossible, l'évaluation de la contribution temporale respective de chaque caractéristique composant la cible.

S'inspirant du paradigme de changement de Schönwälder (2006) qui permet de prendre en compte cet aspect de l'intégration des caractéristiques, deux types de tâches incluant des cibles visuelles définies de façon redondante ont été utilisés. Dans chaque tâche, l'identité de la cible était dévoilée après le changement de deux caractéristiques d'un seul élément de la scène de recherche; ces changements de caractéristiques étaient séparés par un laps de temps variable. Cette asynchronie entre les caractéristiques a permis d'évaluer la contribution respective de chaque caractéristique constituant la cible. Trois caractéristiques différentes, à savoir la couleur, l'orientation et le mouvement local (i.e., tous les éléments à l'écran bougent horizontalement sur une courte distance d'une façon constante), étaient couplées en trois paires différentes. Dans la première tâche, les participants devaient réagir à n'importe quel changement se produisant dans la scène de recherche (tâche de détection des changements de caractéristiques), alors que, dans la seconde tâche, les participants devaient réagir uniquement a certaines combinaisons spécifiques de caractéristiques définies au début de l'expérience (tâche de conjonction des changements de caractéristiques).

Ce paradigme impliquant des changements a révélé que les caractéristiques visuelles ne présentent pas la même latence de traitement. La tâche de détection de changement de caractéristiques a démontré que la couleur doit changer environ 20ms après l'orientation et le mouvement local pour être au mieux intégrés, alors que l'orientation et le mouvement local sont de façon optimale lorsque ces deux caractéristiques changent simultanément. De plus, le fait que des violations de la RMI (Miller, 1986) ont pu être observées pour chaque combinaison de caractéristiques, mais pas nécessairement lorsque les caractéristiques changent simultanément, contredisent de récentes études sur la détection de cibles définies de façon redondante (p. ex., Poom, 2009) démontrant que certaines combinaisons de caractéristiques, comme par exemple le mouvement et la couleur, ne sont pas traitées selon un modèle parallèle coactif.

Ces observations mettent aussi en question la forme actuelle du modèle de sommation des cartes de saillance (comme la Recherche Guidée [Wolfe, 1994], voir plus haut) qui postule implicitement que le traitement des caractéristiques visuelles commence simultanément. Si l'on assume que le développement du signal de saillance au niveau des cartes de saillance spécifiques à chaque caractéristique, corrélé au traitement du signal, est constamment reporté sur la carte de saillance générale comme le propose un modèle de traitement parallèle coactif (p. ex., Miller, 1982), deux caractéristiques nécessitant le même temps de traitement génèreront approximativement à chaque instant de leur traitement une quantité comparable de signal de saillance. Cependant, si les deux caractéristiques ne présent pas la même vitesse de traitement, la contribution respective de chaque caractéristique au signal de saillance commun devient de plus en plus asymétrique en fonction du temps passé. Dans ce cas, la quantité de signal de saillance nécessaire pour déclencher la détection de la cible est atteinte plus tard que lorsque les caractéristiques ont la même vitesse de traitement. Bien qu'atteignant plus vite le seuil de détection qu'une cible définie par une seule caractéristique, une cible définie de façon redondante dont les caractéristiques ont une vitesse de traitement différent n'atteint pas le seuil de détection assez vite pour générer des violations significatives de la RMI, comme observé dans de récentes études présentant simultanément tous les stimuli (p. ex., Poom, 2009). Retarder le traitement de la caractéristique la plus rapide permettrait de rééquilibrer la contribution asymétrique des caractéristiques présentant des vitesses de traitement différentes au signal de saillance commun au niveau de la carte de saillance générale. Au niveau de la tâche de détection des changements, des violations de la RMI seraient par conséquent observées lorsque les caractéristiques change de manière asynchrone, comme démontré dans l'Expérience 1 du chapitre 3.

En revanche, lorsque la tâche demande un traitement des caractéristiques plus profond, comme l'identification d'une conjonction de caractéristiques (Expérience 2), les participants prennent plus de temps pour répondre à la même cible redondante que dans une tâche de détection. De plus, les temps de réaction les plus longs sont systématiquement rencontrés lorsque les caractéristiques changent simultanément et diminuent en fonction du laps de temps séparant les changements de caractéristiques.

Néanmoins, ces observations ne contredisent pas l'hypothèse d'une vitesse de traitement asynchrone des caractéristiques. Le fait que les temps de réaction sont plus longs dans la tâche de conjonction de changements suggère que l'identification des caractéristiques requiert plus de ressources cognitives que de simplement détecter ces mêmes caractéristiques. Cependant, ces ressources semblent être limitées. Lorsque plusieurs caractéristiques doivent être identifiées simultanément, les ressources cognitives ne suffisent pas pour les traiter à la même vitesse que lorsqu'une seule caractéristique doit être identifiée. Ce chevauchement dans le traitement des caractéristiques conduit à un ralentissement général du système de traitement. Un changement simultané des caractéristiques génère un chevauchement maximal dans le traitement, alors qu'un laps de temps entre les changements des caractéristiques réduit ce chevauchement, permettant ainsi à la caractéristique qui change en premier d'être déjà (partiellement) traitée avant le changement de la seconde caractéristique. Par conséquent, le temps de réaction diminue en fonction de la taille du laps de temps entre les changements de caractéristiques.

Suivant ce raisonnement, le chevauchement du traitement des caractéristiques est toujours maximal lorsque ces dernières changent simultanément, et ce indépendamment de leur vitesse de traitement relative. Toutefois, cette dernière influence la diminution des temps de réaction liée à la taille du laps de temps entre les changements des caractéristiques. Lorsque les deux caractéristiques présentent la même vitesse de traitement, la diminution de la zone de chevauchement est similaire quelle que soit la caractéristique qui change en premier. Due à cette particularité, les temps de réaction diminuent de façon symétrique en fonction de la taille du laps de temps entre les changements des caractéristiques. En revanche, dans le cas d'une vitesse de traitement asynchrone, le pattern des temps de réaction est différent. Lorsque la caractéristique à la vitesse de traitement la plus rapide change en premier, le chevauchement de traitement des caractéristiques diminue plus vite (comparé à la caractéristique ayant la vitesse de traitement la plus lente), causant par conséquent une réduction plus forte du temps de réaction associé à la taille du laps de temps entre les changements des caractéristiques. Cette hypothèse est soutenue par la comparaison des pentes pour chaque caractéristique qui change en premier dans chaque paradigme. Selon cette analyse, les résultats ont montré que le mouvement local semble être traité plus vite que la couleur, l'orientation plus vite que le mouvement local, alors que la couleur et l'orientation semble être traités à la même vitesse.

Les conclusions du chapitre 3 suggèrent donc que les caractéristiques visuelles ne sont pas traitées à la même vitesse. De plus, la vitesse de traitement relative dépend des besoins de la tâche. Au niveau des tâches de détection de changements des caractéristiques, la couleur semble être traitée plus vite que l'orientation et le mouvement, alors que un pattern différent et moins clair émerge des tâches de conjonction de changements de caractéristiques. Ces observations sont cohérentes avec d'autres études démontrant que la vitesse de traitement est liée au type de tâche (Adams & Mamassian, 2004; Bedell et al., 2003; Clifford, Arnold & Pearson, 2003).

Le chapitre 4 aborde l'intégration des caractéristiques multisensorielles avec une méthodologie similaire que dans le chapitre 3. Dans l'Expérience 1, un son et un ensemble de stimuli visuels ont été présentés aux participants dont les instructions étaient de réagir à n'importe quel changement. Dans les essais incluant un seul changement, soit la fréquence du son, soit la couleur d'un seul élément visuel changeait, alors que, dans les essais incluant un changement redondant, le son et la couleur d'un élément changeaient simultanément. Les résultats ont montré que les changements redondants étaient significativement plus vite détectés que des changements simples, produisant des gains de redondances ainsi que des violations de la RMI (Miller, 19892), confirmant ainsi le traitement parallèle coactif des caractéristiques multisensorielles (p. ex., Diederich & Colonius, 2004; Gondan et al., 2005; Miller, 1982, 1986).

L’expérience 2 emploie la procédure complète du paradigme de détection de changements des caractéristiques (à savoir un laps de temps entre les changements des caractéristiques des cibles redondantes), et a démontré que, malgré que les temps de réaction les plus rapides sont trouvés lorsque les caractéristiques changent simultanément, plus de violations de la RMI sont observées lorsque la couleur change en même temps ou 20 à 40ms avant le son. Ces résultats sont cohérents avec certaines données comportementales (p. ex., Diederich & Colonius, 2004) et neurophysiologiques (p. ex., Molholm et al., 2006) démontrant un traitement plus rapide des signaux auditifs que visuels.

Ensemble, les résultats des chapitres 3 et 4 conduisent à deux suppositions principales. Premièrement, l’intégration des caractéristiques semble être sensible à la vitesse de traitement des caractéristiques. Les modèles cognitifs évaluant ou basé sur l’intégration des caractéristiques devrait donc prendre en compte cette caractéristique en compte (comme une version modifiée de la Recherche Guidée esquissée dans le chapitre 3). Deuxièmement, ces conclusions fournissent un support additionnel en faveur d’un traitement supramodal (i.e., indépendant) des caractéristiques (p. ex. Wright & Ward, 2008) au niveau de la tâche de détection des caractéristiques (comme développé dans le chapitre 2). Parce que les paradigmes uni- et multimodaux employant la même méthodologie génèrent des résultats pointant dans la même direction, il semble raisonnable de supposer qu’un seul mécanisme peut être responsable du traitement de caractéristiques intra- et intermodales. De plus, ce mécanisme pourrait être basé sur une carte de saillance générale supramodale, au niveau de laquelle les signaux de saillance provenant des caractéristiques des différentes modalités sensorielles seraient intégrés (un concept similaire est proposé par Wright et Ward, 2008), et qui guiderait l’attention en direction de l’objet le plus saillant. Toutefois, une telle carte de saillance générale implique que l’espace externe soit représenté indépendamment des coordonnées de référence de chaque modalité sensorielle (à savoir centrées par rapport à l’œil pour la vision, à la tête pour l’audition et au corps pour la proprioception). Cette suggestion est soutenue par des recherches récentes démontrant que la plupart des neurones d’une sous-structure du cortex pariétal postérieur, l’aire intrapariétale ventrale, répondent aux stimuli visuels et auditifs ayant la même origine spatiale (Schlack et al., 2005). De plus, les mouvements d’approche manuelle in direction de cibles visuelles, auditives, proprioceptives et imaginaires semblent utiliser une même représentation de l’espace externe (Pouget et al., 2002). D’après ces études, l’existence d’une carte de saillance supramodale basée sur des coordonnées spatiales « standardisées » n’est donc pas inconcevable.

9.2. Un mécanisme similaire de contrôle de l’orientation des foyers attentionnel et oculaire

Les expériences rapportées dans le chapitre 5 visent à investiguer le mécanisme de contrôle du système oculomoteur. Comme proposé pour l’orientation de l’attention, par exemple dans la Recherche Guidée (Wolfe, 1994), un mécanisme possible pour le contrôle des mouvements oculaires pourrait être basé sur un signal spatial de saillance. Si c’est effectivement le cas, une cible définie de façon redondante, à cause de son signal spatial de saillance plus important, devrait générer une saccade plus rapidement qu’une cible simple.

Les résultats de la tâche de détection de caractéristiques de l’Expérience 1 soutiennent cette hypothèse en montrant que, si des mouvements oculaires sont produits durant la présentation de la scène de recherche, les cibles redondantes présentent des latences saccadiques plus courtes que les cibles simples. De plus, des gains de redondance ainsi que des violations de la RMI (Miller, 1982) ont été observés pour les latences saccadiques, fournissant la preuve que les deux caractéristiques définissant la cible redondante contribuent au signal de saillance responsable du déclenchement de la saccade.

Cette conclusion est confirmée par l’Expérience 2 démontrant que le signal général de saillance provient effectivement de la sommation spatiale des signaux de saillance générés par les deux caractéristiques constituant la cible. Lorsque les deux caractéristiques sont physiquement séparées (deux éléments distincts portant chacun l’une des caractéristiques), leurs latences saccadiques ne produisent ni gains de redondance, ni violations de la RMI.

Finalement, les expériences du chapitre 5 démontrent que l’usage des mouvements oculaires dépend des besoins de la tâche; détecter une cible redondante (tâche de détection de caractéristiques) requiert de moins bouger les yeux que d’identifier cette même cible (tâche de conjonction de caractéristiques, similaire à la tâche de conjonction de changements des caractéristiques présentées au chapitre 3). De plus, comparer les paramètres oculomoteurs entre les deux tâches révèle que les latences saccadiques sont encore plus courtes dans la tâche de conjonction que dans la tâche de détection. Ces résultats suggèrent par conséquent que le contrôle du système oculaire basé sur un signal de saillance peut être modulé par la tâche (à savoir l'identification de la combinaison définissant la cible), et suggère que ce mécanisme pourrait être envisagé comme le contrôle par défaut des mouvements oculaires.

Bien que ces résultats suggèrent fortement que les mouvements oculaires, comme l'attention, sont guidés par un signal de saillance spatial, cela n'implique pas nécessairement que les systèmes attentionel et oculomoteur n'en forment qu'un. En effet, il a été démontré que les foyers attentionel et oculaire peuvent être bougés indépendamment l'un de l'autre (p. ex., 1980; Posner et al., 1978, 1980), ce qui suggère plutôt que les systèmes attentionel et oculomoteur sont interdépendants (Wright & Ward, 2008), partageant des mécanismes, comme le guidage par saillance spatiale, et des ressources communes, comme certaines structures cérébrales (p. ex., Beauchamps et al., 2001; Corbetta et al., 1998; Nobre et al., 2000) à certains moments du traitement des caractéristiques.

9.3. Effet de l'expérience sur le traitement des caractéristiques

Le chapitre 6 du présent travail vise à investiguer si l'expérience peut modifier la façon dont les caractéristiques sont traitées dans une tâche de détection des caractéristiques visuelles, comme peut être améliorée la discrimination d'objets ou de caractéristiques visuels (p. ex., Fahle, 2004; Lu et al., 2005; McKee & Westheimer, 1978; Schoups et al., 1995). Pour adresser cette question, une tâche de détection de caractéristiques incluant des cibles redondantes définies par leur couleur et leur orientation a été répétée lors de quatre sessions différentes au cours d'une même semaine.

Les résultats indiquent que l'expérience améliore significativement la détection de n'importe quelle cible entre la première et la deuxième session et reste constante jusqu'à la dernière session. De plus, les gains de redondance ne sont pas affectés par l'expérience, alors que la magnitude des violations de la RMI, attestation d'un traitement parallèle coactif, augmente pour atteindre le niveau de significativité à la troisième session. Ce résultat suggère que le traitement des caractéristiques n'est pas fixe mais peut être modifié par l'expérience. Par conséquent, des preuves d'un traitement parallèle coactif sont plus faciles à observer chez des participants expérimentés.

Néanmoins, être capable de démontrer qu'un modèle parallèle coactif semble gouverner le traitement des caractéristiques visuelles suggère que le système perceptuel emploie ce mécanisme en temps normal. Le fait que des violations de la RMI n'apparaissent que dans la troisième session peut être attribué au cadre expérimental artificiel. Parce que donner une réponse manuelle symbolique sur une représentation simplifiée d'une scène visuelle a peu de correspondance dans la vie quotidienne, les participants naïfs ont besoin de se familiariser avec la tâche pour que leurs réponses reflètent un traitement parallèle coactif des caractéristiques visuelles.

9.4. Les caractéristiques visuelles comme indice d'un souvenir implicite

Les observations des chapitres précédents suggèrent donc que les caractéristiques, indépendamment de leur origine sensorielle, sont traitées selon un mécanisme basé sur un modèle parallèle coactif et prenant en compte tant leurs propriétés spatiales que temporelles. De plus, des preuves de ce traitement peuvent nécessiter une certaine habituation pour être révélées. Cependant, dans la vie quotidienne, le contexte dans lequel se situe un objet à trouver est rarement autant homogène que dans les expériences rapportées dans les chapitres précédents, et la scène visuelle est par conséquent plus riche en détails, rendant l'objet-cible plus difficile à repérer. Néanmoins, si cette situation est répétée, la richesse du contexte pourrait servir d'indice pour retrouver cet objet-cible. D'un autre côté, si ce contexte répété change, retrouver l'objet-cible devient plus difficile. Par exemple, si tous les produits de votre armoire de salle de bain sont mélangés, retrouver votre laque ou votre rasoir vous prendra certainement plus de temps que s'ils étaient à leur place habituelle.

Le chapitre 7 se focalise sur le rôle des caractéristiques visuelles lors de l'apprentissage entre les caractéristiques des distracteurs et leur configuration spatiale dans la scène visuelle. Il a été démontré que répéter le contexte dans lequel se trouve une cible améliore les performances dans une tâche de détection visuelle (p. ex., Chun & Jiang, 1998). Bien que cet effet, appelé « indiçage » par le contexte (*contextual cueing*), a été attribué exclusivement à un souvenir basé sur la répétition de la configuration spatiale des objets dans la scène visuelle, des études récentes démontrent que les caractéristiques des objets, comme la couleur, peuvent aussi servir à se souvenir de la position de la cible (p. ex., Huang, 2006).

Pour pouvoir examiner la contribution relative des différentes caractéristiques dans l'indiçage par le contexte, huit expériences ont été conçues. La première d'entre elles était une réplication de l'expérience séminale de Chun et Jiang (1998) et a servi de ligne de base pour les expériences suivantes. La tâche des participants consistait à trouver une cible entourée de distracteurs ayant plusieurs orientations différentes (un T parmi des L) et à indiquer de quel côté (gauche ou droite) la cible était penchée. De plus, la moitié des essais présentés durant le premier bloc étaient répétés à l'identique tout au long de l'expérience, alors que l'autre moitié des essais était renouvelés à chaque bloc. L'indiçage par le contexte fait référence au bénéfice au niveau des temps de réaction pour les essais se répétant, en comparaison avec les essais ne se répétant pas. Comme attendu, la première expérience a répliqué les résultats obtenus par Chun & Jiang (1998), démontrant une croissance constant de l'indiçage par le contexte. Les sept expériences suivantes sont basées sur le même paradigme, mais impliquent un changement d'une ou deux caractéristiques au milieu de la session expérimentale. Si une caractéristique peut effectivement indiquer la position de la cible, un changement de cette dernière devrait par conséquent empêcher le développement de cet effet, comme démontré par Huang (2006) pour la couleur.

Les résultats ont démontré que les caractéristiques n'apportent pas la même contribution à l'indiçage par le contexte. La couleur semble être la seule caractéristique dont le changement empêche le développement de l'indiçage par le contexte. Cependant, lorsque seule la luminance ou la teinte change, l'indiçage par le contexte ne s'en voit pas affecté, suggérant que cet effet observé avec un changement de couleur résulte d'une interaction entre les aspects chromatique et achromatique de la couleur.

Changer l'orientation des distracteurs n'altère pas l'indiçage par le contexte. Cela semble être dû au rôle particulier de cette caractéristique dans la scène visuelle. L'hétérogénéité de l'orientation des distracteurs est en effet à la source de la difficulté de la recherche. Si tous les distracteurs partageaient la même orientation, la cible serait beaucoup plus facile à détecter (p.ex., Wolfe & Horowitz, 2004) et se souvenir des caractéristiques des distracteurs deviendrait superflu. Dû à son lien étroit avec l'efficacité de la recherche, l'orientation des distracteurs ne peut donc pas servir efficacement d'indice sur la position de la cible.

Bien que n'étant pas étroitement impliqué dans la tâche comme l'est l'orientation, la taille ne sert pas directement d'indice sur la position de la cible. Changer la taille des objets n'altère en effet pas le développement de l'indiçage par le contexte. Néanmoins, la taille, ainsi que la luminance, ont un effet particulier. Comparé à l'expérience de base, les expériences impliquant des objets de différentes tailles ou luminances présentent un développement de l'indiçage par le contexte qui tend par la suite à diminuer rapidement. A la place d'une progression linéaire, comme observée dans l'expérience de base, l'indiçage par le contexte prend une forme parabolique. Un examen des résultats montrent que les temps de réaction pour les essais se répétant et ne se répétant pas présentent des patterns différents. Les temps de réaction pour les essais se répétant diminuent plus fortement que dans la réplication et se stabilisent relativement tôt dans l'expérience, suggérant que les participants ont atteint un temps de réaction optimal pour la tâche. Cependant, les temps de réaction pour les essais ne se répétant pas diminuent de façon plus graduée. Par conséquent, l'espace entre les deux courbes augmente rapidement au début de l'expérience, et se réduit par la suite, produisant cette courbe en forme de parabole. D'après ces résultats, à la place d'indiquer directement la position de cible, comme la couleur, la taille et la luminance semble augmenter la richesse de la scène visuelle et mettre en exergue la configuration des distracteurs. Parce que la relation entre les positions de la cible et des distracteurs est rapidement apprise, un changement de ces caractéristiques n'affecte pas l'indiçage par le contexte.

Finalement, un changement des deux caractéristiques définissant la cible, spécialement pour la couleur et l'orientation, n'affecte pas l'indiçage par le contexte. Ces conclusions peuvent être rapprochées des résultats obtenus par Chun et Jiang (1998, Expérience 2) démontrant qu'un changement de l'identité des distracteurs au milieu de l'expérience n'altère pas l'indiçage par le contexte, et suggère par conséquent qu'un changement complet de toutes les caractéristiques des objets équivaut à un changement d'identité des distracteurs. Dû au manque de fiabilité de toutes les caractéristiques des objets, les participants ne comptent que sur la configuration spatiale des distracteurs pour retrouver la cible.

Les résultats du chapitre 7 démontrent donc que les différentes caractéristiques testées contribuent de façon différente à l'indiçage par le contexte. Au cause de son étroite implication dans la tâche, l'orientation ne peut pas indiquer efficacement la position de la cible, tandis que la taille et la luminance génèrent plus de variété dans la scène visuelle, ce qui semble mettre en valeur la configuration spatiale des distracteurs. La couleur est la seule caractéristique qui a pu altérer l'indiçage par le contexte, confirmant ainsi que la couleur peut efficacement indiquer la position de la cible (p. ex., Huang, 2006). Etonnamment, un changement simultané de luminance et de teinte est nécessaire pour provoquer cet effet, suggérant que les participants encodent les deux aspects de la couleur durant la phase d'apprentissage.

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