Psychological Research (2011) 75:452–465
DOI 10.1007/s00426-011-0352-5

REVIEW

The role of saccades in multitasking: towards an output-related view of eye movements

Lynn Huestegge

Received: 15 December 2010 / Accepted: 2 June 2011 / Published online: 1 July 2011

Abstract The present paper presents an overview of research on the role of saccades in multitasking. Multitasking is known to cause performance costs in terms of increased response times and/or error rates. However, most of the previous research on multitasking was focused on manual and vocal action demands, and the role of eye movements has been largely neglected. As a consequence, saccade execution was mainly considered with respect to its functional role in gathering new visual information (input side of information processing). However, several more recent experiments confirmed that saccades both exhibit and cause dual-task costs in the context of other actions and should thus also be regarded as a response modality (output side of information processing). Theoretical implications as well as several open issues for future research will be outlined.

Introduction

From everyday experience we know that the execution of more than one task at a time is more difficult than performing one task alone. Multitasking typically leads to costs in terms of more errors and/or slower responses (e.g., Pashler, 1994). An important goal of multitasking research has been to understand the underlying mechanisms that cause these costs. For a long time, research has mainly focussed on two specific response modalities, namely manual and vocal responses (Pashler, 1998). As a consequence, current multitasking theories are mainly based on data derived from a quite limited range of response modalities, which raises the question as to what extent these theories really cover general (instead of modality-specific) principles of multitasking. For example, oculomotor responses (eye movements) were mainly regarded as a by-product of input-related processes (see Sect. "Modeling the role of eye movements in multitasking"). The neglect of eye movements in the context of multitasking may partly be due to the impression that we constantly move our eyes and body concurrently without experiencing difficulties arising from the performance of an additional task. Furthermore, costs and labor associated with eye movement recording might have played a role.

Already in nineteenth century Solomons and Stein (1896) reported classic dual-task experiments based on self-observation data with respect to reading prose while writing at the same time (see also Shaffer, 1975; Spelke, Hirst, & Neisser, 1976). One apparent difficulty with such studies is that despite a certain ecological validity, complex continuous tasks do not allow the experimenter to control the timing of stimulus events, which in turn makes it difficult to determine the cognitive mechanisms of multitasking (e.g., Broadbent, 1982). Another crucial problem is that reading always involves the execution of eye movements. However, this additional motor demand was not explicitly considered as a further response modality which might potentially interfere with the manual writing task. Instead, Solomons and Stein (1896) concluded that "[e]ye movements here seem to be simply a result of attention" (p. 504). Most likely, it was tacitly assumed that eye movement execution is an effortless, input-related process which should not interfere with the two tasks. This highlights a problematic aspect of multitasking research in general, namely the problem of defining what counts as "one task". We usually do not consider reading (or visual

L. Huestegge (✉)
Institute of Psychology, RWTH Aachen University, Jägerstraße 17/19, 52066 Aachen, Germany
e-mail: lynn.huestegge@psych.rwth-aachen.de

search, etc.) as a dual task, just because eye movements are involved (see Pashler, Carrier, & Hoffman, 1993). One way to deal with such a problematic state of affairs is to gather empirical evidence to decide whether and how saccades interfere with other concurrent (e.g., manual and vocal) response demands. The attempt to answer this question will be the main topic of the present paper.

Input-related versus output-related view of eye movements

The above quotation from Solomons and Stein (1896) is symptomatic of a widespread view of saccades as an indicator of input-related information processing. This is also evident in the term "overt attention" (see Wright & Ward, 2008), which is often used to characterize eye movements, as opposed to "covert attention", which refers to looking out of the corner of one's eye (Posner, 1980). For example, in a common introductory textbook on attention Styles (1997) acknowledges that "visual attention is intimately related to where we are looking and to eye movements", but "[p]erhaps there is nothing much to explain here; we just attend to what we are looking at" (see also Findlay & Gilchrist, 2003, for a critical discussion). Similarly, but with a more optimistic view on the usefulness of studying eye movements, Just and Carpenter (1980) proposed that eye movements basically reflect attention processes associated with the fixated stimulus. Accordingly, they assumed that stimuli are interpreted as soon as they are encountered, and that fixation of a stimulus lasts as long as processing has finished. Although this rather simplistic view of the interplay of attention and eye movements has been challenged (e.g., Henderson, 2005; Kliegl, Nuthmann, & Engbert, 2006; Rayner, 1998, 2009), the underlying assumption that saccades are mainly a reflection of input-related attentional processing remained intact. In the following, we will refer to this as the input-related view of eye movements.

However, the present paper will show that saccades exhibit similar effects as other, more traditionally studied response modalities (e.g., manual or vocal responses) in the context of multitasking. Consequently, this paper advocates the importance of a complimentary, output-related view of eye movements, which highlights the idea that saccades should be viewed no differently than other motor responses, and thus the visual system should be regarded as an "ordinary" response modality. Of course, both accounts are not considered mutually exclusive, but rather as two sides of the same coin.

Experimental multitasking paradigms

One basic characteristic of traditionally studied motor systems (manual, vocal) is that they cause (and are subject to) interference with other concurrent response demands. This was demonstrated by utilizing experimental paradigms which can broadly be subdivided into four categories.

1. The first category consists of the simultaneous execution of two (or more) continuous tasks (see Spelke et al., 1976; Solomons & Stein, 1896). Despite the drawbacks mentioned above, some important questions necessitate utilizing continuous tasks, for example studying adverse effects of talking on the phone while driving (e.g., Strayer, Drews, & Johnson, 2003; Levy, Pashler, & Boer, 2006; Kunar, Carter, Cohen, & Horowitz, 2008).
2. To gain more experimental control over stimuli and cognitive processes, novel paradigms were invented which typically comprised basic sensorimotor tasks consisting of a set of distinct and clearly defined stimuli and responses. For example, a central characteristic of the task switching paradigm is that participants switch between tasks, with a new task starting only after a previous task has been finished (Allport, Styles, & Hsieh, 1994; Rogers & Monsell, 1995; see Kiesel et al., 2010, for a review).
3. Alternatively, the temporal task overlap can be varied systematically by manipulating the stimulus onset asynchrony (SOA) between the two stimuli of the tasks. This procedure is known as the psychological refractory period (PRP) paradigm (Welford, 1952; Pashler, 1994, for a review).
4. Finally, it is possible to present the stimuli for both tasks at the same time, or to use only one stimulus that carries sufficient information for both responses (simultaneous stimulation, e.g., Fagot & Pashler, 1992). Here, dual-task costs are assessed by comparing single- versus dual-task performance. Most of the dual-task studies involving eye movement responses utilized either the PRP paradigm or the simultaneous stimulation paradigm (see below).

Oculomotor and manual movements towards a common target

Most of the scientific studies that were concerned with the simultaneous control of saccades and manual responses analyzed the coordination of both effector systems in the context of reaching and pointing, where we usually direct saccades and manual responses towards one common object. One major aim here is to show how eye movements and corresponding visual feedback guide manual movements. For example, Megaw and Armstrong (1973) reported that latencies of saccades and hand movements towards visual targets were correlated, suggesting that there is interdependence between the two processing systems (see also Posner, Nissen, & Ogden, 1978; Mather & Fisk, 1985; Pelz, Hayhoe, & Loeber, 2001; Johansson, Westling, Backstrom, & Flanagan, 2001; Land & Hayhoe, 2001; Horstmann & Hoffmann, 2005). More specifically, it was argued that data on eye and hand movements in pointing suggest early parallel processing of both motor responses (Prablanc, Echallier, Jeannerod, & Komilis, 1979). Other studies reported evidence for a common control system for both motor systems during co-ordinated ocular and manual tracking of a sinusoidally moving visual target (Mather & Putchat, 1983; see also Vidoni, McCarley, Edwards, & Boyd, 2009).

Interestingly, many studies on saccades and manual movements towards one common object yielded evidence for cross-response facilitation. For example, in tracking tasks the limb seems to assist the eye in producing more accurate ocular tracking (Mather & Lackner, 1980; Mather & Putchat, 1983; Steinbach & Held, 1968). Vice versa, looking at the target typically improves manual accuracy (Prablanc, Echallier, Komilis, et al. 1979). Most likely, the fact that eye movements are initiated and completed faster than manual movements allows the visual system to process information about manual accuracy before pointing is completed, and this sensory feedback can be used for manual fine-tuning (Prablanc et al., 1979; Bekkering & Sailer, 2002; Crawford, Medendorp, & Marotta, 2004). Facilitation in terms of reduced RTs in dual-task conditions compared with single-task conditions was shown for saccades (Lünenburger, Kutz, & Hoffmann, 2000) and for manual responses (Epelboim et al., 1997; Snyder, Calton, Dickinson, & Lawrence, 2002; see also Niechwiej-Szwedo, McIlroy, Green, & Verrier, 2005). However, it should be noted that other studies (some of them not only involving visual, but also auditory target stimuli) reported evidence for dual-task interference in terms of increased saccade RTs, whereas manual responses remained unaffected (Bekkering, Adam, Kingma, Huson, & Whiting, 1994, Experiment 1; Bekkering, Adam, Van der Aarssen, Kigma, & Whiting, 1995; Mather & Fisk, 1985; Pratt, Bekkering, Abrams, & Adam, 1999).

Taken together, it appears as if in the context of reaching/pointing towards a common target, saccades and manual responses do seem to interact. However, there is only little (for saccades) or no (for manual responses) evidence for dual-task interference.

Logically independent oculomotor and manual responses

While the studies reported above addressed a special case of the simultaneous execution of oculomotor and manual responses (i.e., reaching/pointing towards a common target), comparatively little research has been devoted to the study of simultaneously executed saccades and manual responses on a more general level, involving logically independent responses. For example, Malmstrom, Reed, and Weber (1983) conducted a study in which participants performed oscillatory step saccades either with or without a simultaneous go/no-go task which consisted of auditory stimuli and manual responses. They found shorter saccade amplitudes and more saccadic response omissions in dual-task conditions. However, RTs were not reported for both tasks so that it is difficult to draw specific conclusions with respect to the underlying causes of the observed cross-response interference.

A more complete picture can be obtained from a study by Pashler, Carrier, and Hoffman (1993), who conducted a series of PRP experiments. In one task, participants executed a saccade to a visual stimulus, whereas the other task was to respond with a key press to the pitch of a tone. The visual stimulus was either presented after (positive SOA) or prior to the auditory stimulus (negative SOA), but never at the same time. Four experiments were conducted, which mainly differed with respect to the difficulty of the saccade task. Experiment 1 included saccades towards a single transient (left vs. right), whereas participants in Experiment 2 performed a saccade towards one of two peripheral colored patches (the correct response was defined by a prespecified color). In Experiments 3 and 4, saccades were triggered by a central color discrimination task, or a peripheral symbolic discrimination task (execution of a saccade towards the higher digit). Overall, the experiments failed to reveal a typical PRP effect: Whereas in many other task combinations more temporal task overlap (shorter SOA) typically led to a substantial prolongation of the second task (i.e., the PRP effect; see Welford, 1952; Pashler, 1994), the data pattern of these experiments was different. More specifically, saccades were frequently executed before the manual response, even when the stimulus for the saccade task was presented after the stimulus for the manual task (response inversions). Moreover, when these inversions occurred, the manual response (which was the second response in these cases) was not postponed for short SOAs, but rather exhibited decreased latencies. Additionally, there was only a weak co-variation of saccade RTs and manual RTs. Pashler et al., (1993) explained these results by assuming that saccades and manual responses can be executed without much competition for central limited resources. Even though they found evidence for a small increase of saccade RTs for short SOAs, this finding was rather explained in terms of a general reduction of oculomotor efficiency through the presence of the tone-task in close temporal proximity or, alternatively, in terms of temporal uncertainty induced by the SOA variation.

However, three issues pose a challenge for a conclusive interpretation of these data. First, the specific input–output (S-R) modality pairings for the tasks might have provided a general advantage for the saccade task, since the same sensorimotor system (i.e., the visual system) is involved (for the crucial role of S-R modality pairings in multitasking see McLeod & Posner, 1984; Levy & Pashler, 2001; Ruthruff, Hazeltine, & Remington, 2005; Hazeltine, Ruthruff, & Remington, 2006; Stephan & Koch, 2010). Thus, potential differences in the relative ease of S-R modality pairings make any interaction of saccades and manual responses in the Pashler et al. (1993) study difficult to interpret. Second, the PRP paradigm usually involves two tasks which do not substantially differ in their overall RT level. However, here saccades were so fast that even in conditions where the stimulus for the saccade task was presented relatively long after the presentation of the stimulus of the manual task, the saccade response was often given prior to the manual response. This violates a basic prerequisite to a successful interpretation of PRP results, namely that the sequence of responses should at least in the majority of cases be in accordance with the sequence of stimulus presentation (see Sect. "Bottleneck models"). Third, it was argued that the PRP paradigm might generate serial task processing strategies because of the sequential stimulus presentation, and not because the cognitive system is incapable of parallel central processing (Meyer & Kieras, 1997; Navon & Miller, 2002). Finally, it should be noted that the PRP paradigm only captures a portion of performance costs in multitasking. For example, PRP studies that additionally included single-task conditions demonstrated that RT1 and RT2 in PRP trials are (at any SOA) longer than the respective single-task RTs (e.g., Herman & Kantowitz, 1970; Hommel, 1998; Pashler, 1994), suggesting further sources of performance costs in multitasking beyond a central response selection bottleneck. In sum, these limitations make it difficult to finally interpret the findings by Pashler et al. (1993) as evidence for a lack of central interference between saccades and manual responses.

Experiment 2 in the study of Bekkering et al. (1994, see Sect. "Oculomotor and manual movements towards a common target") also combined saccades and manual responses towards independent targets. Unlike Pashler et al. (1993), they utilized simultaneous stimulation methodology. Participants made key press responses to visual stimuli while saccades were (vs. were not) executed. Here, neither manual nor saccade responses exhibited significant dual-task costs. However, this null result might have occurred due to a lack of statistical power, since the manual RTs showed a tendency of dual-task costs of about 15 ms with 12 participants. Additionally, visual stimuli were used to trigger both responses, which again might have resulted in unbalanced stimulus–response modality pairings for both tasks. These heterogeneous demands for both tasks might have concealed any dual-task costs.

As a response to these limitations, we conducted a dual-task study in which we utilized auditory (instead of visual) stimulation for both responses within the simultaneous stimulation paradigm (Huestegge & Koch, 2009). Participants responded to a single imperative auditory stimulus with either a left versus right key press (manual task), a left versus right saccade (saccade task), or both. Additionally, we varied the spatial compatibility between both responses across four experiments. Overall, the results indicated dual-task costs (in terms of prolonged RTs) for both response modalities. These costs were consistently greater for manual responses. Given that a single stimulus triggered both responses (implying common perceptual processing), the dual-task costs seemed to occur at a relatively late, output-related stage of information processing, which further supports the output-related view of saccades. Furthermore, the overall size of dual-task costs (in terms of RTs and errors) was closely related to the spatial compatibility between responses, suggesting that response-code conflict (in terms of response confusability) played a major role in determining the size of dual-task costs (Koch, 2009).

More evidence for mutual interference between saccades and manual responses comes from a recent study by Jonikaitis, Schubert, and Deubel (2010). They had participants reach and look towards different locations while the time interval between the movement initiation cues was systematically varied. As a result, they demonstrated significant dual-task costs, i.e., participants were slower to initiate a saccade or manual response if they were planning another movement at the same time. More importantly, however, in another experiment the authors added a probe discrimination task at the locations of the (oculomotor and manual) movement goals. Interestingly, despite the dual-task costs reflected in movement RTs, there seemed to be no delay of corresponding attention shifts, consequently ruling out input-related attentional goal selection as a bottleneck. Instead, the source of dual-task costs rather seemed to be located at later, probably more output-related stages of response processing. In line with these assumptions, Jonikaitis and Deubel (2011) reported additional data which demonstrated that attentional resources are allocated independently to separate targets for oculomotor and manual movements, suggesting that goal selection for both movements can occur in parallel.

Hodgson, Müller, and O'Leary (1999) conducted a study in which they investigated the effect of eye movements on a concurrent manual response which was (vs. was not) directed towards a common target. More specifically, they compared the performance of cued manual key release and reaching responses in conditions with versus without the simultaneous execution of saccades. Whereas the key for the key release task was not located at the saccade target position, the reaching tasks involved a manual response towards a common target position. They reported that the additional execution of a saccade delayed simultaneous key release RTs, whereas reaching RTs were unaffected. Overall, this pattern is in line with the result pattern across studies reported above, namely that coordinated eye-hand movements towards a common target leads to less interference (or even facilitation effects) compared with conditions in which responses are logically independent.

Sharikadze, Cong, Staude, Deubel, and Wolf (2009) reported data on an interesting special case of manual movements. In their study, participants made reflexive saccades to peripheral targets while performing a rhythmic manual tapping task. However, they found no evidence for dual-task costs, probably because rhythmic tapping involves a fairly automatic response mode.

Taken together, the studies referred to above converge in that dual-task costs are generally greater in tasks with logically independent responses (separate targets) as compared to tasks in which both responses are co-ordinated by a common target. However, based on the observations reported by Pashler et al. (1993) it should be noted that robust dual-response interference effects are only observed when saccades are not triggered by peripheral visual target stimuli, a condition which is probably special in that it may allow saccades to bypass any processing bottlenecks. Nevertheless, under most other conditions there seems to be robust evidence for substantial interference between saccades and concurrent manual responses (cross-modal response interference). This shows that saccades exhibit similar interference effects in multitasking as do other, more traditionally studied response modalities. Therefore, the visual system can also be viewed as an ordinary response modality.

Interference between saccades and manual responses: implications

The finding of robust interference between saccades and manual responses has several important implications for the interpretation of data in paradigms that utilize spatially distributed visual stimuli, for example, in the Simon task, cueing paradigms, as well as in visual search and scene perception. In fact, based on the results so far it seems as if these paradigms may actually be considered as dual-task settings, as long as participants are not explicitly instructed to remain fixated. Indeed, recent studies suggested that eye movements play an important role in these paradigms.

For example, Buetti and Kerzel (2010) studied the contribution of eye movements to the Simon effect. The Simon effect refers to the finding that manual RTs are faster when the stimulus occurs in the same (vs. incongruent) relative location as the response, even if the stimulus location is task-irrelevant (Simon, 1969). Buetti and Kerzel used a variant of the Simon task and either instructed participants to execute saccades or to remain fixated. The results suggested that some portion of the Simon effect is related to the fact that in incongruent conditions, participants initially look towards the stimulus location and then redirect their gaze towards the correct response location. Thus, it appears that the additional occurrence of eye movements may prolong manual RTs in conditions where the stimulus is spatially incompatible with the response location.

The potential importance of saccades for explaining effects on manual RTs in cueing paradigms was recently demonstrated in our lab (Huestegge & Adam, 2011). More specifically, we analyzed the role of saccades in manual response preparation by utilizing the finger precueing task (Miller, 1982), in which participants pressed one of four response keys with one of four fingers (two of each hand) in response to a visual stimulus that appeared at one of four display positions, two in the left and two in the right visual hemifield (responses were always compatible with the stimulus). Stimulus and response locations were arranged in a line. Prior to the stimulus, either a neutral cue (baseline, appearing at all four positions), a hand cue (corresponding to the two left vs. the two right positions), or a finger cue (corresponding to the two inner vs. two outer positions) was presented. Note that in the finger cue condition, the cue consisted of two stimuli in both visual hemifields, often triggering saccades which were either compatible or incompatible with the subsequent stimulus location. Crucially, participants either remained fixated or moved their eyes freely. The results demonstrated that the fixation condition modulated the pattern of cueing effects. More specifically, the typical manual RT advantage of hand cues over finger cues vanished when trials in the finger cue condition were excluded in which saccades during the cueing interval were directed in the opposite direction of the subsequently required manual response. Thus, interference between saccades and manual responses affected manual motor preparation.

Taken together, these studies suggest that some manual RT effects that were previously attributed to cognitive phenomena (e.g., compatibility effects, perceptual or manual motor grouping effects) may at least partly also result from cross-response interference effects between saccades and manual responses. This indicates that the output-related view of saccades potentially has serious implications for other studies in the field of experimental psychology where eye movements occur but are neglected as a potential source of influence for effects in other (e.g., manual) domains.

Given that cross-modal response interference played a major role in these basic paradigms, similar effects might also arise in more complex everyday tasks. Thus, these phenomena may also have implications for tasks like visual orientation, scene perception, and navigation in traffic. For example, whenever we look towards a potentially hazardous object in traffic, we are supposed to steer away from it, which likely involves the execution of incompatible saccades and manual responses (e.g., see Müsseler, Aschersleben, Arning, & Proctor, 2009 for a related study which did not involve eye tracking). Corresponding interference effects may negatively affect traffic safety, which calls for a closer study of cross-modal response interference effects in more natural settings.

Interference between eye movements and perceptual tasks: a special case of multitasking

While the dual-task studies reported so far mainly focussed on the execution of saccades in the context of an additional task which involved a speeded response, numerous studies involved the execution of a saccade while being engaged in a perceptual task, which typically involves a non-speeded response after saccade execution. On the one hand, many of these studies mainly addressed the interplay of covert attention and eye movements (see Huestegge & Koch, 2010b, for a review). On the other hand, some studies directly addressed the issue of dual-task interference between eye movements and perceptual tasks. For example, in a recent study by Carbone and Schneider (2010) participants performed saccades towards visual targets while attending to briefly presented visual stimuli. They found that saccade latencies increased in dual-task conditions, especially when the stimuli for both tasks were presented in close temporal proximity and when the attention task included a more complex stimulus pattern (see also Tibber, Grant, & Morgan, 2009). However, they did not find evidence for dual-task interference when the attention task consisted of auditory stimuli, suggesting that visual attention limitations (instead of more general central limitations) play an important role in this particular paradigm. In a similar design, Evens and Ludwig (2010) reported data on the simultaneous execution of antisaccades (i.e., saccades directed away from a transient in the periphery) during a perceptual task which involved the detection of a luminance change. Dual-task costs in terms of increased saccade RTs were observed, which were attributed to a general increase in the response criterion for saccade generation in dual-task conditions (see also Roberts, Hager, & Heron, 1994; Stuyven, Van der Goten, Vandierendonck, Claeys, & Crevits, 2000; Vandierendonck, Deschuyteneer, Depoorter, & Drieghe, 2008). Another study reported worse performance in a number processing task during the simultaneous execution of saccades (Irwin & Thomas, 2007). More specifically, participants responded to a magnitude or parity judgment task while executing no, short, or long saccades. As a result, they found increased magnitude comparison RTs for long (vs. short) saccades when the eyes moved from right to left, a phenomenon which was termed cognitive suppression during saccades. Although the magnitude judgment task may not qualify as a perceptual task, the results may be interpreted as evidence for interference between saccades and specific central processing mechanisms.

Further evidence for interference between saccades and perceptual tasks comes from a study of our lab (Huestegge & Koch, 2010b). Participants executed saccades towards briefly presented target letters in the periphery. Additionally, we either deleted the central fixation point 200 ms prior to target presentation (gap condition), or the central fixation point remained present throughout the trial (overlap condition). Typically, saccade RTs are faster in gap compared with overlap conditions (i.e., the gap effect, Saslow, 1967). Interestingly, the ability to take advantage of the temporal gap was reduced when participants simultaneously attended to the identity of the peripheral letters compared with a single-task condition in which the letters could be ignored. Taken together, these findings clearly suggest that saccade control can suffer from dual-task interference even when the secondary task does not require an immediate motor response.

Modeling the role of eye movements in multitasking

While the previous sections mainly focussed on empirical evidence regarding the role of saccades in dual-task situations, I will now outline traditional and current theoretical efforts to model cognitive processing during multitasking. Specifically, I will evaluate these models with respect to their capability to capture the role of eye movements. From a historical perspective, conceptual models of multitasking can be divided into at least three different groups: resource models, bottleneck models, and crosstalk models.

Resource models

Initially, the metaphor of limited resources during multitasking generated single resource theories. The main idea behind single-resource theory is that our mind contains one unitary source of mental capacity (or resource), and whenever two tasks demand more resources than offered, capacity needs to be shared. Eventually, this leads to performance decrements in at least one of the two tasks. The idea of capacity sharing was introduced by Kahneman

(1973) and further developed by Norman and Bobrow (1975; see also Navon & Miller, 2002; Tombu & Jolicoeur, 2003, for more recent variants). However, while the latter accounts did not specifically refer to eye movements, Kahneman (1973) clearly tended towards an input-oriented view of saccades, namely that the functional role of eye movements is to select task-relevant visual input or to prioritize spatially distributed auditory information (cross-modal attention biasing).

As a response to the growing evidence for the claim that dual-task performance is determined by the specific input- and output modalities involved in the two tasks, it was proposed that the mind may comprise multiple resources instead of only one unitary capacity. Elaborate versions of this idea were presented by Navon and Gopher (1979) and Wickens (1980, 1984, 2002). With respect to eye movements, both models entertained an input-related view. More specifically, Navon and Gopher (1979) underlined the ability of the system to manipulate the input quality for competing visual processes by fixating specific regions within our visual environment. Similarly, Wickens (e.g., 2002) assumed that eye movements mainly reflect visual processing, which is regarded as a perceptual modality, whereas only the "usual suspects" (manual and vocal responses) were considered as response modalities.

In sum, it seems as if resource theory in general did not explicitly consider eye movements as a response modality, but rather tended towards an input-related view of saccades. Nevertheless, it appears principally conceivable to explain saccade-based dual-task costs in terms of competition for limited resources. However, it has been shown that the pattern of results obtained with the simultaneous execution of saccades and manual responses did not quite match the specific predictions derived from resource theory (Huestegge & Koch, 2009). Furthermore, a major general drawback of resource models is their circular explanatory nature: Whenever dual-task costs arise, these are explained by referring to resource limitations, which appears to be an unproductive heuristic for specifying the underlying cognitive architecture of multitasking (e.g., Allport, 1980; Navon, 1984; Neumann, 1987). Finally, the assumption of limited resources may appear implausible on a general level given that our brain is essentially characterized by simultaneous parallel processing (Neumann, 1987).

Bottleneck models

Within a second class of multitasking models, the bottleneck models, task processing is conceived of as a series of distinct stages, such as perceptual processing, response selection, and response execution. These models mainly assume that some mental operations during task processing can only be processed serially (i.e., for one task at a time), while other processing stages may occur in parallel. Empirical evidence from numerous PRP studies involving the experimental manipulation of the various processing stages in both tasks suggested that primarily the response selection stage (i.e., the stage for deciding which response corresponds to a given stimulus based on instructed task rules) acts as a central bottleneck. This observation gave rise to the most prominent version of the family of bottleneck models, the central bottleneck model (Pashler, 1994). According to this model response selection must be devoted to only one response at a time, so that processing of the second task is suspended until response selection in the first task has been finished (Pashler, 1994). Interestingly, the PRP effect occurs even when sensory and motor modalities are distinct for the two tasks (e.g., an auditory-manual Task 1 and a visual-vocal Task 2), suggesting that the central response selection stage is basically an a-modal origin to the dual-task costs (e.g., Welford, 1952; Pashler, 1994).

As outlined in Sect. "Logically independent oculomotor and manual responses", there was no convincing evidence for a central response selection bottleneck for the simultaneous execution of saccades and manual responses in the Pashler et al., (1993) study. However, given the limitations of this particular study (see "Logically independent oculomotor and manual responses") it appears that more empirical evidence is needed to finally decide the issue of serial versus parallel processing of saccades in the context of multitasking. Nevertheless, it should be noted that at least in principal the bottleneck model was open to an output-related view of saccades, since it triggered the first study to ask "whether the central response selection mechanism is invoked each time an eye movement is produced" (Pashler et al., 1993, p. 55).

More recent models of multitasking extended the core idea of serial central processing from the central bottleneck model to account for more complex multitasking situations. However, these extensions either did not explicitly discuss eye movements (Byrne & Anderson, 2001) or referred to eye movements as a means to facilitate perception and as a reflection of visual attention (Salvucci & Taatgen, 2008), which clearly represents an input-oriented view of saccades.

As an alternative to the both bottleneck and resource models, Meyer and Kieras (1997) introduced a theoretical framework in which the possibility of parallel processing at any stage of information processing is an integral part. While it resembles bottleneck models by assuming that task processing for each task is accomplished in multiple stages, it emphasizes executive processes and task strategies as major determinants of dual-task performance. As a consequence, the PRP effect is explained in terms of a strategic rather than a generic bottleneck. More importantly, the model explicitly acknowledges the occurrence of eye movements by stressing that previous dual-task research "tended to ignore possible artifacts caused by eye movements" (Meyer & Kieras, 1997, p. 52). Consequently, the architecture of their model explicitly contains an "ocular motor processor", similar to vocal and manual motor processors. All three motor processors receive input from the same cognitive processor, which applies individual task rules, but also maintains task priorities and coordinates progress on concurrent tasks. Thus, interference between saccades and manual responses may be explained in terms of costs associated with specific task priorities and task coordination processes.

However, a closer look at the model reveals that despite this possibility, Meyer and Kieras (1997) maintained an input-related view of eye movements, which precludes them from explicitly considering corresponding interference phenomena. More specifically, they postulated that "latencies of intermediate eye movements must be evaluated rigorously to determine whether response-selection processes for primary and secondary tasks actually have an opportunity to overlap temporally" (Meyer & Kieras, 1997, p. 52), showing that eye movements are mainly viewed as an integral part of the individual (vocal or manual) tasks. For example, they assumed that eye movements may be used as a means to prioritize a specific task by directing the eyes towards the corresponding stimulus first (instead of looking at a stimulus related to a secondary task). The special role of eye movements is also evident in their overall model architecture, where vocal and manual motor processors, but not the ocular motor processor, are assumed to directly affect the task environment (see also Logan & Gordon, 2001, who proposed a related dual-task model, but without referring to eye movements).

Crosstalk models

While the bottleneck models clearly focus on determining specific processing stages (or a-modal mental operations) relevant for the occurrence of dual-task costs, models built around the crosstalk metaphor rather focus on the specific content of the two tasks. One crucial presupposition of the crosstalk metaphor is parallel processing. In engineering, the notion of crosstalk refers to a content-dependent degradation of two adjacent communication channels, and Kinsbourne (1981) suggested utilizing this concept as a metaphor for dual-task processing. More specifically, crosstalk in cognitive psychology refers to any interference between simultaneous tasks that share physical features or involve associated conceptual dimensions, such as overlapping stimulus and/or response features or dimensions (Navon & Miller, 1987). For example, when two tasks require left/right responses, this might result in response-based conflict, especially when the two tasks require the activation of different codes at the same time ("outcome conflict", see Navon, 1985; Navon & Miller, 1987).

In a recent study, we tested the parallel processing assumption of the crosstalk model in the context of simultaneously executed saccades and manual responses (Huestegge & Koch, 2010a). We utilized a crossed-response incompatibility paradigm which avoided some of the drawbacks of the PRP paradigm (see Sect. "Logically independent oculomotor and manual responses") while maintaining the possibility to systematically manipulate the temporal task overlap. In general, we used a similar setup as in Huestegge and Koch (2009). More specifically, we implemented a spatially incompatible stimulus–response mapping for one task (e.g., manual task) but not for the other (saccade task). Critically, inverting these mappings varied the temporal task overlap in dual-task conditions while keeping spatial incompatibility across responses constant. Interestingly, the observed dual-task costs for both response modalities (replicating Huestegge & Koch, 2009) were not affected by an increase of temporal task overlap, which would have been predicted by a serial processing model. Instead, this finding could be interpreted as evidence for parallel response selection.

Since one of the preconditions of the crosstalk metaphor (parallel processing) was validated, we developed a corresponding conceptual framework based on these results (Huestegge & Koch, 2010a; see Fig. 1). Although this model still incorporates different processing stages, i.e., perceptual processing, mapping selection (as opposed to response selection in the individual tasks), and response execution, it focuses on the activation of content-based codes (representing task-relevant features like response modalities and spatial response characteristics) needed for a successful completion of the tasks. The crucial cognitive challenge while being engaged in multitasking is to bind together these codes in accordance with the pre-defined task rules. Note that unlike traditional crosstalk accounts our model does not highlight the conflict between codes of two ongoing tasks, but rather claims that the main source of crosstalk derives from a conflict between the selection of a current binding pattern and the persisting activation of previous, conflicting binding patterns. More specifically, the conflict between these binding patterns mainly arises from the fact that the same task attributes are relevant for both tasks across all trials, but need to be remapped from trial to trial in accordance with the task instructions. Thus, in its present state the focus of this framework is relatively specific (compared with previous multitasking models), because it focuses on trial-to-trial variations in interference and on the role of conflicting binding patterns for a specific combination of effectors (i.e., saccades and manual responses).

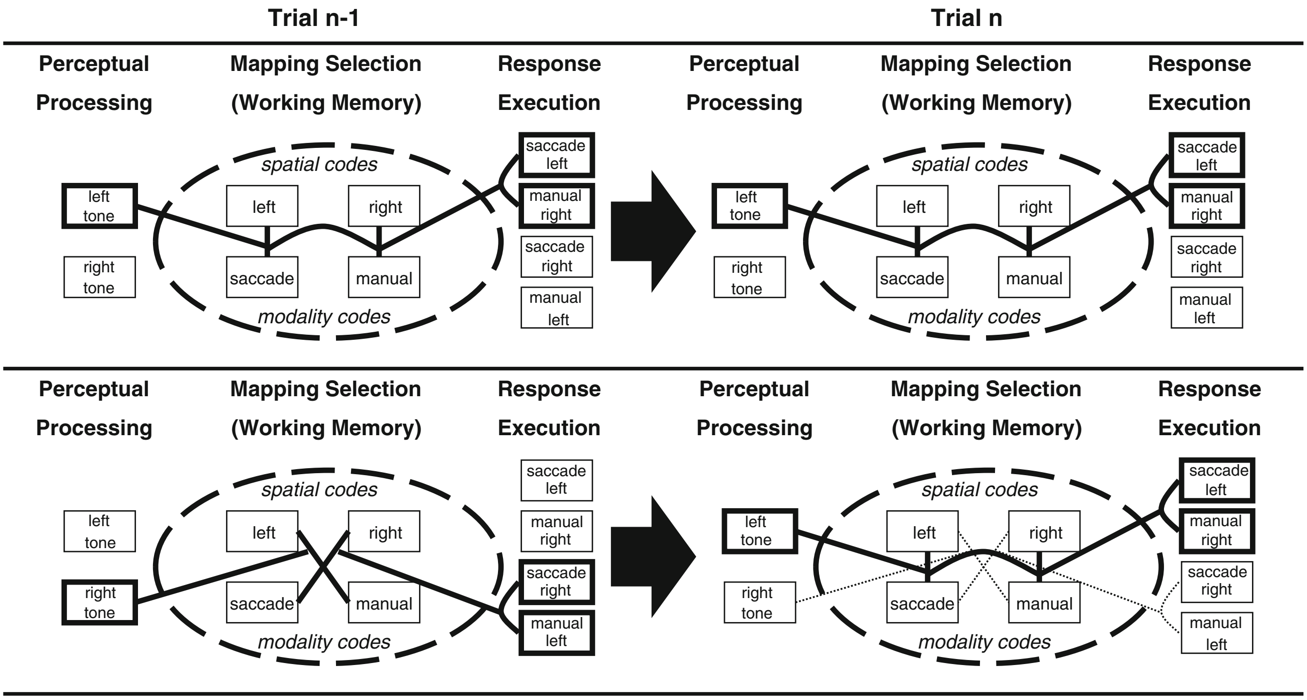

Fig. 1 The model above represents a task in which a spatially compatible saccade and an incompatible manual response are triggered by a lateralized auditory stimulus. In the upper row, the binding pattern of the present trial (n) corresponds to that in the previous trial (n-1), so that mapping selection is comparatively easy. However, in the lower row binding patterns diverge between trials, so that the present pattern must overcome persisting activation of the conflicting previous pattern (*thin dotted lines*). This is associated with performance costs

Nevertheless, we believe that this framework can principally be extended (by introducing further assumptions) to account for a variety of other, more general dual-task phenomena. For example, previous multitasking frameworks (e.g., Meyer & Kieras, 1997; Pashler, 1994) can easily explain more general interference, which may also occur in the first trial and even when there is no content overlap between two tasks. If we additionally assume that the time to activate a specific binding pattern increases as a function of its complexity (e.g., single-task conditions require a binding of two attributes, whereas dual-task conditions require a binding of four attributes), this additional assumption could probably account for such general dual-task related costs. Furthermore, effects of S-R compatibility, dual-task cost asymmetries, and strategic effects (e.g., prioritization of one task over another; see also Israel & Cohen, this volume) may be implemented by assuming variable a priori activation of attributes or connection strength (e.g., stronger a priori activation of a spatial code which corresponds to the spatial stimulus location, or stronger a priori activation of a specific modality code). Thus, we think that this conceptual framework may probably represent an interesting alternative to previous conceptions of multitasking, because it highlights parallel processing and the specific content of the tasks in a unique way. Therefore, the model may be helpful in generating new and informative research questions. However, it should be clear from the description of the framework that many potential implications of this model need to be tested explicitly in the future to further broaden its empirical and theoretical base. Taken together, the framework may provide a novel take on our understanding of some dual-task related phenomena, but only future research will tell whether a more fully developed model can represent a viable alternative to the established models, which up to now rest on a much more solid data base.

Open issues for future research

In this section, some important research issues that remained largely unanswered so far will be highlighted more closely to stimulate future research.

1. One open theoretical issue relates to potential implications of the findings reported here for current views of attention. While some textbooks devoted to attention appear to neglect eye movements altogether (e.g., Ward, 2004), others explicitly underline the importance (or even primacy) of the oculomotor system and its inherent characteristics to understand attention (e.g., Findlay & Gilchrist, 2003). However, even the latter view still maintains a mainly input-oriented take

on the visual system by stressing its functional role, namely the selection of relevant input information in the context of a given task.

In contrast, other researchers posited that attention is closely coupled to motor processes (e.g., the premotor theory of attention, see Rizzolatti, Riggio, Rascola, & Umiltà, 1987, and the Visual Attention Model, see Schneider & Deubel, 2002). Most of the corresponding research is based on experiments combining speeded response tasks with non-speeded perceptual tasks (see Sect. "Interference between eye movements and perceptual tasks: A special case of multitasking"). However, a combination between this research tradition and research on multitasking involving the simultaneous execution of two speeded tasks seems to be lacking.

A related important conceptual issue is the question of how to interpret most of the reviewed evidence in favor of dual-response costs in the context of saccades. More specifically, in most studies reported here it is not clear as to what degree such costs would equally arise from covert movements of attention (instead of overt eye movements). An empirical way to deal with this issue would be to conduct empirical studies explicitly devoted to delineating between perceptual/input-related costs and response-/output-related costs. In contrast, a theory-based way to address this problem (when viewed from the perspective of the premotor theory of attention) could also be to question the validity of the distinction between input- and output-related processing altogether, at least with respect to visuomotor processing. Based on the perspectives offered in the present review, it appears that a closer co-operation between the streams of research devoted to overt/covert attention on the one hand and multitasking on the other hand might lead to a more complete picture of the complex interrelation between attention, eye movements, and sources of conflict in multitasking.

2. A second open question is to what extent dual-task costs arise when saccades are performed in conjunction with other, non-manual responses, e.g., vocal responses, foot responses, etc. In line with previous research suggesting that the specific couplings of input-and output modalities in multitasking play a major role (e.g., Hazeltine et al., 2006; Hazeltine & Wifall, this volume; Huestegge & Hazeltine, this volume; Stelzel & Schubert, this volume; Stelzel, Schumacher, Schubert, & D'Esposito, 2006), one might expect that combining saccades (which are usually executed first) with other response modalities might yield different effects on the pattern of dual-task costs. This could have serious implications for modeling multitasking processes in general. Furthermore, since the overall results reported here seem to suggest that eye movements indeed interfere with other responses, it could be interesting to determine the consequences of performing triple tasks (e.g., executing saccades while performing a manual and a vocal task) in comparison with dual-task settings.
3. A third issue that has not been addressed with respect to saccades is the question of how dual-task skills are acquired. Hazeltine et al. (2006) suggest that different input–output modality pairings produce different learning characteristics. For example, the fact that we are training eye-hand coordination whenever we reach for objects might to some extent generalize to other situations involving eye and hand movements, so that learning to produce compounds of saccades and manual responses might be easier as compared with other response compounds involving saccades.
4. Another issue that has not yet received much attention is the question of more applied implications of cross-response interference between saccades and other types of responses. One potentially interesting field that was not addressed empirically yet is navigation in traffic (see Sect. "Interference between saccades and manual responses: implications"), where we move our eyes while at the same time producing manual steering and foot braking responses (see Müsseler et al., 2009; Atchley, Dressel, Jones, Burson, & Marshall, this volume; Huestegge, Skottke, Anders, Debus, & Müsseler, 2010). Corresponding interference might have safety–critical implications and thus should be studied more closely.

Another interesting applied field for studying interference between saccades and vocal responses could be oral reading, where the eyes move along lines of text while vocal output is produced at the same time (see Huestegge, 2010; Huestegge, Radach, Corbic, & Huestegge, 2009). Since it is known that fixation durations are prolonged during oral as compared with silent reading (Rayner, 2009), it appears interesting to determine as to what extent basic interference between saccades and vocal responses contributes to this phenomenon.

5. Beside the general evidence for saccade-related dual-task interference, some of the studies of eye movements during reaching reported evidence for facilitation (dual-task benefits, see Sect. "Oculomotor and manual movements towards a common target"). However, it remained unclear what conditions exactly determine whether the simultaneous execution of two responses yields interference versus facilitation. Interestingly, resource models as well as bottleneck frameworks principally rule out the possibility of dual-task benefits. Even the traditional crosstalk metaphor implies interference effects when information between

two processing streams overlap, whereas facilitation should not be possible. Only the Huestegge and Koch model (2010a, Fig. 1) offers a reasonable perspective to explain dual-task benefits by assuming that the activation of a response code may be facilitated either through pre-activation of the same code in previous trials or through co-activation by other, closely connected response codes in a current trial. This calls for empirical studies to systematically address the issue of dual-task facilitation versus interference within an appropriate explanatory framework.

6. Another potentially interesting way to learn more about the underlying processes of saccade execution in the context of other responses would involve using the task-switching paradigm (see Stephan & Koch, this volume; Wylie, this volume). The studies reported so far mainly utilized the PRP paradigm or the simultaneous onset paradigm. However, an explicit manipulation of inter-trial sequences would offer an interesting possibility to test some of the implications of models that stress the importance of inter-trial interference (e.g., Huestegge & Koch, 2010a).
7. One potentially important conceptual distinction that has not been addressed in this review so far is that between (a) eye movements as an explicitly instructed part of the task set (explicit eye movements) and (b) eye movements as either a necessity for making a response or as a not explicitly instructed by-product induced by the nature of the task (implicit eye movements). Most of the experiments reported in this review belong to the former category, where it makes intuitively sense to think of eye movements as responses. However, in most situations eye movements are not explicitly instructed, and thus it appears conceivable that cost patterns could be different between implicit and explicit eye movements. From a theoretical view, for explicit eye movements one would probably expect individuals to monitor their own responses to detect errors (e.g., Botvinick, M., Braver, T., Barch, D. Carter, C., & Cohen, J., 2001), an executive process that might yield greater costs when compared with implicit eye movements. In line with this view, it has been shown that an explicit instruction of a task sets (vs. an instruction that did not explicitly refer to a task set) can yield measurable effects on performance (e.g., Dreisbach, Goschke, & Haider, 2006). Interestingly, it has also been demonstrated that even implicit eye movements may be associated with costs. For example, Boot, Kramer, Becic, Wiegmann, and Kubose (2006) showed that visual search performance improves considerably when participants were instructed to avoid eye movements. Taken together, it appears promising to directly address the issue of dual-response costs associated with implicit versus explicit eye movements in future research.
8. Finally, up to now there seems to be only sparse research on the neurophysiological underpinnings of the simultaneous execution of saccades and other types of responses. A lot of research so far has been devoted to understanding the cortical control of saccades and manual movements in separation, and some research addressed eye-hand coordination during reaching towards a common target (e.g., Brown, Kessler, Hefter, Cooke, & Freund, 1993; Baker, Donoghue, & Sanes, 1999; Battaglia-Mayer et al., 2000; Carey, 2000; Snyder, Batista, & Andersen, 2000; Ramnani, Toni, Passingham, & Haggard, 2001; Buneo, Jarvis, Batista, & Andersen, 2002; Crawford, Medendorp, & Marotta, 2004; Nitschke, Arp, Stavrou, Erdmann, & Heide, 2005; Land, 2005; Battaglia-Mayer, Archambault, & Caminiti, 2006). Evidence from these lesion and brain imaging studies suggest that a supramodal representation for eye-hand interaction is mainly controlled by a parieto-cerebellar network. However, there is still a clear lack of research on dual-response interference on a more general level, i.e., when the two responses are not logically co-ordinated by a common target. For example, brain imaging studies which examined visual and auditory tasks under single- and dual-task conditions reported regions in dorsal premotor, dorsal prefrontal and superior parietal cortices related to dual-task processing across tasks and modalities (see Marois & Ivanoff, 2005; Schumacher et al., this volume), probably reflecting a neural mechanism for a general, central response selection mechanism. Unfortunately, we do not know yet whether similar networks are involved when other response modalities are combined. Taken together, the neural basis of coordinating saccades and manual responses without a common target remained elusive yet.

Conclusions

Taken together, the studies reported in this review suggest that eye movements can be regarded as an "ordinary" response modality, since they show similar patterns of interference as do other, more traditionally studied response modalities (e.g., manual or vocal). Thus, it seems justified to proclaim that an output-related view of saccades should complement the well-established input-related view. From this perspective, our visuomotor system appears to be quite special in that it represents a natural integrator of the domains of perception and action (Huestegge & Koch, 2010b). On a more general level, only future research will tell as to what extent current theories of multitasking, which are based on data from a limited selection of response modalities, will generalize to other types of responses, including eye movements.

References

Allport, D. A. (1980). Attention and performance. In G. L. Claxton (Ed.), *Cognitive psychology: new directions* (pp. 112–153). London: Routledge.

Allport, A., Styles, E. A., & Hsieh, S. (1994). Shifting intentional set: exploring the dynamic control of tasks. In C. Umilta & M. Moscovitch (Eds.), *Attention and performance XV* (pp. 421–452). Cambridge: MIT Press.

Baker, J. T., Donoghue, J. P., & Sanes, J. N. (1999). Gaze direction modulates finger movement activation patterns in human cerebral cortex. *Journal of Neuroscience, 19*, 10044–10052.

Battaglia-Mayer, A., Archambault, P. S., & Caminiti, R. (2006). The cortical network for eye-hand coordination and its relevance to understanding motor disorders of parietal patients. *Neuropsychologia, 44*, 2607–2620.

Battaglia-Mayer, A., Ferraina, S., Mitsuda, T., Marconi, B., Genovesio, A., Onorati, P., et al. (2000). Early coding of reaching in the parietooccipital cortex. *Journal of Neurophysiology, 83*, 2374–2391.

Bekkering, H., Adam, J. J., Kingma, H., Huson, A., & Whiting, H. T. A. (1994). Reaction time latencies of eye and hand movements in single- and dual-task conditions. *Experimental Brain Research, 97*, 471–476.

Bekkering, H., Adam, J. J., van den Aarssen, A., Kingma, H., & Whiting, H. T. (1995). Interference between saccadic eye and goal-directed hand movements. *Experimental Brain Research, 106*, 475–484.

Bekkering, H., & Sailer, U. (2002). Commentary: coordination of eye and hand in time and space. *Progress in Brain Research, 140*, 365–373.

Boot, W. R., Kramer, A. F., Becic, E., Wiegmann, D. A., & Kubose, T. (2006). Detecting transient changes in dynamic displays: the more you look, the less you see. *Human Factors, 48*, 759–773.

Botvinick, M., Braver, T., Barch, D., Carter, C., & Cohen, J. (2001). Conflict monitoring and cognitive control. *Psychological Review, 108*, 624–652.

Broadbent, D. E. (1982). Task combination and selective intake of information. *Acta Psychologica, 50*, 253–290.

Brown, S. H., Kessler, K. R., Hefter, H., Cooke, J. D., & Freund, H.-J. (1993). Role of the cerebellum in visuomotor coordination. *Experimental Brain Research, 94*, 478–488.

Buetti, S., & Kerzel, D. (2010). Effects of saccades and response type on the Simon effect: if you look at the stimulus, the Simon effect may be gone. *The Quarterly Journal of Experimental Psychology, 63*, 2172–2189.

Buneo, C. A., Jarvis, M. R., Batista, A. P., & Andersen, R. A. (2002). Direct visuomotor transformations for reaching. *Nature, 416*, 632–636.

Byrne, M. D., & Anderson, J. R. (2001). Serial modules in parallel: the psychological refractory period and perfect time-sharing. *Psychological Review, 108*, 847–869.

Carbone, E., & Schneider, W. X. (2010). The control of stimulus-driven saccades is subject not to central, but to visual attention limitations. *Attention, Perception, and Psychophysics, 72*, 2168–2175.

Carey, D. P. (2000). Eye-hand coordination: eye to hand or hand to eye? *Current Biology, 10*, 416–419.

Crawford, J. D., Medendorp, W. P., & Marotta, J. J. (2004). Spatial transformations for eye-hand coordination. *Journal of Neurophysiology, 92*, 10–19.

Dreisbach, G., Goschke, T., & Haider, H. (2006). Implicit task sets in task switching? *Journal of Experimental Psychology Learning, Memory, and Cognition, 32*, 1221–1233.

Epelboim, J., Steinman, R. M., Kowler, E., Pizlo, Z., Erkelens, C. J., & Collewijn, H. (1997). Gaze-shift dynamics in two kinds of sequential looking tasks. *Vision Research, 37*, 2597–2607.

Evens, D. R., & Ludwig, C. J. (2010). Dual-task costs and benefits in anti-saccade performance. *Experimental Brain Research, 205*, 545–557.

Fagot, C., & Pashler, H. (1992). Making two responses to a single object: implications for the central attentional bottleneck. *Journal of Experimental Psychology Human Perception and Performance, 18*, 1058–1079.

Findlay, J. M., & Gilchrist, I. D. (2003). *Active vision: the psychology of looking and seeing*. Oxford: Oxford University Press.

Hazeltine, E., Ruthruff, E., & Remington, R. W. (2006). The role of input and output modality pairings in dual-task performance: evidence for content-dependent central interference. *Cognitive Psychology, 52*, 291–345.

Henderson, J. M. (2005). Human gaze control during real-world scene perception. *Trends in Cognitive Science, 7*, 498–504.

Herman, L. M., & Kantowitz, B. H. (1970). The psychological refractory period effect: only half the double-stimulation story? *Psychological Bulletin, 73*, 74–88.

Hodgson, T. L., Müller, H. J., & O'Leary, M. J. (1999). Attentional localization prior to simple and directed manual responses. *Perception & Psychophysics, 61*, 308–321.

Hommel, B. (1998). Automatic stimulus-response translation in dual-task performance. *Journal of Experimental Psychology Human Perception and Performance, 24*, 1368–1384.

Horstmann, A., & Hoffmann, K. P. (2005). Target selection in eye-hand coordination: do we reach to where we look or do we look to where we reach? *Experimental Brain Research, 167*, 187–195.

Huestegge, L. (2010). Effects of vowel length on gaze durations in silent and oral reading. *Journal of Eye Movement Research, 3(5):*5, 1–18.

Huestegge, L., & Adam, J. J. (2011). Oculomotor interference during manual response preparation: evidence from the response cueing paradigm. *Attention, Perception, and Psychophysics, 73*, 702–707.

Huestegge, L., & Koch, I. (2009). Dual-task crosstalk between saccades and manual responses. *Journal of Experimental Psychology Human Perception and Performance, 35*, 352–362.

Huestegge, L., & Koch, I. (2010a). Crossmodal action selection: evidence from dual-task compatibility. *Memory and Cognition, 38*, 493–501.

Huestegge, L., & Koch, I. (2010b). Fixation disengagement enhances peripheral perceptual processing: evidence for a perceptual gap effect. *Experimental Brain Research, 201*, 631–640.

Huestegge, L., Radach, R., Corbic, D., & Huestegge, S. M. (2009). Oculomotor and linguistic determinants of reading development: a longitudinal study. *Vision Research, 49*, 2948–2959.

Huestegge, L., Skottke, E.-M., Anders, S., Debus, G., & Müsseler, J. (2010). The development of hazard perception: dissociation of visual orientation and hazard processing. *Transportation Research, 13F*, 1–8.

Irwin, D. E., & Thomas, L. E. (2007). The effect of saccades on number processing. *Perception and Psychophysics, 69*, 450–458.

Johansson, R. S., Westling, G., Backstrom, A., & Flanagan, J. R. (2001). Eye-hand coordination in object manipulation. *The Journal of Neuroscience, 21*, 6917–6932.

Jonikaitis, D. & Deubel, H. (2011). Parallel and independent allocation of attention to eye and hand movement goals. *Psychological Science* (in press).

Jonikaitis, D., Schubert, T., & Deubel, H. (2010). Preparing coordinated eye and hand movements: dual task costs are not attentional. *Journal of Vision, 10*(14), 1–17.

Just, M. A., & Carpenter, P. A. (1980). A theory of reading: from eye fixations to comprehension. *Psychological Review, 87*, 329–354.

Kahneman, D. (1973). *Attention and effort*. Englewood Cliffs: Prentice Hall.

Kiesel, A., Steinhauser, M., Wendt, M., Falkenstein, M., Jost, K., Philipp, A. M., et al. (2010). Control and interference in task switching—a review. *Psychological Bulletin, 136*, 849–874.

Kinsbourne, M. (1981). Single channel theory. In D. H. Holding (Ed.), *Human skills* (pp. 65–89). Chichester: Wiley.

Kliegl, R., Nuthmann, A., & Engbert, R. (2006). Tracking the mind during reading: the influence of past, present, and future words on fixation durations. *Journal of Experimental Psychology General, 135*, 12–35.

Koch, I. (2009). The role of crosstalk in dual-task performance: evidence from manipulating response-set overlap. *Psychological Research, 73*, 417–424.

Kunar, M. A., Carter, R., Cohen, M., & Horowitz, T. S. (2008). Telephone conversation impairs sustained visual attention via a central bottleneck. *Psychonomic Bulletin and Review, 15*, 1135–1140.

Land, M. F. (2005). Eye-hand coordination learning a new trick. *Current Biology, 15*, 955–956.

Land, M. F., & Hayhoe, M. M. (2001). In what ways do eye movements contribute to everyday activities? *Vision Research, 41*, 3559–3565.

Levy, J., & Pashler, H. (2001). Is dual-task slowing instruction dependent. *Journal of Experimental Psychology Human Perception and Performance, 27*, 862–869.

Levy, J., Pashler, H., & Boer, E. (2006). Central interference in driving: is there any stopping the psychological refractory period? *Psychological Science, 17*, 228–235.

Logan, G. D., & Gordon, R. D. (2001). Executive control of visual attention in dual-task situations. *Psychological Review, 108*, 393–434.

Lünenburger, L., Kutz, D. F., & Hoffmann, K. P. (2000). Influence of arm movements on saccades in humans. *European Journal of Neuroscience, 12*, 4107–4116.

Malmstrom, F. V., Reed, L. E., & Weber, R. J. (1983). Saccadic eye movements during a concurrent auditory task. *Bulletin of the Psychonomic Society, 27*, 31–34.

Marois, R., & Ivanoff, J. (2005). Capacity limits of information processing in the brain. *Trends in Cognitive Sciences, 9*, 296–304.

Mather, J., & Fisk, J. (1985). Orienting to targets by looking and pointing: parallels and interactions in ocular and manual performance. *Quarterly Journal of Experimental Psychology, 37A*, 315–338.

Mather, J. A., & Lackner, J. R. (1980). Visual tracking of active and passive movements of the hand. *Quarterly Journal of Experimental Psychology, 32*, 307–315.

Mather, J. A., & Putchat, C. (1983). Parallel ocular and manual tracking responses to a continuously moving visual target. *Journal of Motor Behavior, 15*, 29–38.

McLeod, P., & Posner, M. I. (1984). Privileged loops from percept to act. In H. Bouma & D. G. Bouwhuis (Eds.), *Attention and Performance X. Control of language processes* (pp. 55–66), Hove, UK: Lawrence Erlbaum Associates.

Megaw, E. D., & Armstrong, W. (1973). Individual and simultaneous tracking of a step input by the horizontal saccadic eye movement and manual control systems. *Journal of Experimental Psychology, 100*, 18–28.

Meyer, D. E., & Kieras, D. W. (1997). A computational theory of executive cognitive processes and multiple-task performance: Part 1. *Basic mechanisms. Psychological Review, 104*, 3–65.

Miller, J. (1982). Discrete versus continuous models of human information processing: in search of partial output. *Journal of Experimental Psychology Human Perception and Performance, 8*, 273–296.

Müsseler, J., Aschersleben, G., Arning, K., & Proctor, R. (2009). Reversed effects of spatial compatibility in natural scenes. *American Journal of Psychology, 122*, 325–336.

Navon, D. (1984). Resources—A theoretical soupstone? *Psychological Review, 91*, 216–234.

Navon, D. (1985). Attention division or attention sharing. In M. I. Posner & O. S. M. Marin (Eds.), *Attention and performance XI* (pp. 133–146). Hillsdale, NJ: Erlbaum.

Navon, D., & Gopher, D. (1979). On the economy of the human information processing system. *Psychological Review, 86*, 214–255.

Navon, D., & Miller, J. (1987). Role of outcome conflict in dual-task interference. *Journal of Experimental Psychology Human Perception and Performance, 13*, 435–448.

Navon, D., & Miller, J. (2002). Queuing or sharing. A critical evaluation of the single-bottleneck notion. *Cognitive Psychology, 44*, 193–251.

Neumann, O. (1987). Beyond capacity: a functional view of attention. In H. Heuer & A. F. Sanders (Eds.), *Perspectives on perception and action* (pp. 361–394). Hillsdale: Erlbaum.

Niechwiej-Szwedo, E., McIlroy, W. E., Green, R. E. A., & Verrier, M. C. (2005). The effect of directional compatibility on the response latencies of ocular and manual movements. *Experimental Brain Research, 162*, 220–229.

Nitschke, M. F., Arp, T., Stavrou, G., Erdmann, C., & Heide, W. (2005). The cerebellum in the cerebro-cerebellar network fort he control of eye and hand movements—an fMRI study. *Progress in Brain Research, 148*, 151–164.

Norman, D. A., & Bobrow, D. G. (1975). On data limited and resource limited processes. *Cognitive Psychology, 7*, 44–64.

Pashler, H. (1994). Dual-task interference in simple tasks: data and theory. *Psychological Bulletin, 116*, 220–244.

Pashler, H. (1998). *The psychology of attention*. Cambridge: MIT Press.

Pashler, H., Carrier, M., & Hoffman, J. (1993). Saccadic eye movements and dual-task interference. *Quarterly Journal of Experimental Psychology, 46A*, 51–82.

Pelz, J., Hayhoe, M. M., & Loeber, R. (2001). The coordination of eye, head, and hand movements in a natural task. *Experimental Brain Research, 139*, 266–277.

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology, 32*, 3–25.

Posner, M. I., Nissen, M. J., & Ogden, W. C. (1978). Attended and unattended processing modes: the role of set for spatial location. In H. L. Pick Jr. & I. J. Saltzman (Eds.), *Modes of perceiving and processing information* (pp. 137–157). Hillsdale: Erlbaum.

Prablanc, C., Echallier, J. E., Jeannerod, M., & Komilis, E. (1979a). Optimal response of eye and hand motor systems in pointing at a visual target. II. Static and dynamic visual cues in the control of hand movement. *Biological Cybernetics, 35*, 183–187.

Prablanc, C., Echallier, J. F., Komilis, E., & Jeannerod, M. (1979b). Optimal response of eye and hand motor systems in pointing at a visual target. I. Spatio-temporal characteristics of eye and hand movements and their relationships when varying the amount of visual information. *Biological Cybernetics, 35*, 113–124.

Pratt, J., Bekkering, H., Abrams, R. A., & Adam, J. (1999). The gap effect for spatially oriented responses. *Acta Psychologica, 102*, 1–12.

Ramnani, N., Toni, I., Passingham, R. E., & Haggard, P. (2001). The cerebellum and parietal cortex play a specific role in coordination: a PET study. *NeuroImage, 14*, 899–911.

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin, 124*, 372–422.

Rayner, K. (2009). Eye movements and attention in reading, scene perception, and visual search. *Quarterly Journal of Experimental Psychology, 62*, 1457–1506.

Rizzolatti, G., Riggio, L., Dascola, I., & Umilta, C. (1987). Reorienting attention across the horizontal and vertical meridians: evidence in favor of a premotor theory of attention. *Neuropsychologia, 25*, 31–40.

Roberts, R. J., Hager, L. D., & Heron, C. (1994). Prefrontal cognitive processes: working memory and inhibition in the antisaccade task. *Journal of Experimental Psychology General, 123*, 374–393.

Rogers, R. D., & Monsell, S. (1995). The cost of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology General, 124*, 207–231.

Ruthruff, E., Hazeltine, E., & Remington, R. W. (2005). What causes residual dual-task interference after practice? *Psychological Research, 70*, 494–503.

Salvucci, D. D., & Taatgen, N. A. (2008). Threaded cognition: an integrated theory of concurrent multitasking. *Psychological Review, 115*, 101–130.

Saslow, M. G. (1967). Effects of components of displacement-step stimuli upon latency for saccadic eye movement. *Journal of the Optical Society of America, 57*, 1024–1029.

Schneider, W. X., & Deubel, H. (2002). Selection-for-perception and selection-for-spatial-motor-action are coupled by visual attention: a review of recent findings and new evidence from stimulus-driven saccade control. In W. Prinz & B. Hommel (Eds.), *Attention and performance XIX: common mechanisms in perception and action* (pp. 609–627). Oxford: Oxford University Press.

Shaffer, L. H. (1975). Multiple attention in continuous verbal tasks. In P. M. A. Rabbitt & S. Dornic (Eds.), *Attention and performance V* (pp. 157–167). New York: Academic Press.

Sharikadze, M., Cong, D. K., Staude, G., Deubel, H., & Wolf, W. (2009). Dual-tasking: is manual tapping independent of concurrently executed saccades? *Brain Research, 1283*, 41–49.

Simon, J. R. (1969). Reactions toward the source of stimulation. *Journal of Experimental Psychology, 81*, 174–176.

Snyder, L. H., Batista, A. P., & Andersen, R. A. (2000). Saccade-related activity in the parietal reach region. *Journal of Neurophysiology, 83*, 1099–1102.

Snyder, L. H., Calton, J. L., Dickinson, A. R., & Lawrence, B. M. (2002). Eye-hand coordination: saccades are faster when accompanied by a coordinated arm movement. *Journal of Neurophysiology, 87*, 2279–2286.

Solomons, L. M., & Stein, G. (1896). Normal motor automatism. *Psychological Review, 3*, 492–512.

Spelke, E. S., Hirst, W., & Neisser, U. (1976). Skills of divided attention. *Cognition, 4*, 215–230.

Steinbach, M. J., & Held, R. (1968). Eye tracking of observer-generated target movements. *Science, 161*, 187–188.

Stelzel, C., Schumacher, E., Schubert, T., & D'Esposito, M. (2006). The neural effect of stimulus-response modality compatibility on dual-task performance: an fMRI study. *Psychological Research, 70*, 514–525.

Stephan, D. N., & Koch, I. (2010). Central crosstalk in task switching: Evidence from manipulating input-output modality compatibility. *Journal of Experimental Psychology Learning, Memory, and Cognition, 36*, 1075–1081.

Strayer, D., Drews, F., & Johnston, W. (2003). Cell-phone induced failures of visual attention during simulated driving. *Journal of Experimental Psychology Applied, 9*, 23–32.

Stuyven, E., Van der Goten, K., Vandierendonck, A., Claeys, K., & Crevits, L. (2000). The effect of cognitive load on saccadic eye movements. *Acta Psychologica, 104*, 69–85.

Styles, E. A. (1997). *The psychology of attention*. Hove: Psychology Press.

Tibber, M. S., Grant, S., & Morgan, M. J. (2009). Oculomotor responses and visuospatial perceptual judgments compete for common limited resources. *Journal of Vision, 9*, 1–13.

Tombu, M., & Jolicoeur, P. (2003). A central capacity sharing model of dual-task performance. *Journal of Experimental Psychology Human Perception and Performance, 29*, 3–18.

Vandierendonck, A., Deschuyteneer, M., Depoorter, A., & Drieghe, D. (2008). Input monitoring and response selection as components of executive control in pro-saccades and anti-saccades. *Psychological Research, 72*, 1–11.

Vidoni, E. D., McCarley, J. S., Edwards, J. D., & Boyd, L. A. (2009). Manual and oculomotor performance develop contemporaneously but independently during continuous tracking. *Experimental Brain Research, 195*, 611–620.

Ward, A. (2004). *Attention: a neuropsychological approach*. New York: Psychology Press.

Welford, A. T. (1952). The "psychological refractory period" and the timing of high-speed performance—a review and a theory. *British Journal of Psychology, 434*, 2–19.

Wickens, C. D. (1980). The structure of attentional resources. In R. Nickerson (Ed.), *Attention and performance VIII* (pp. 239–257). Hillsdale: Erlbaum.

Wickens, C. D. (1984). Processing resources in attention. In R. Parasuraman & D. R. Davies (Eds.), *Varieties of attention* (pp. 63–102). Orlando: Academic Press.

Wickens, C. D. (2002). Multiple resources and performance prediction. *Theoretical Issues in Ergonomics Science, 3*, 159–177.

Wright, R. D., & Ward, L. M. (2008). *Orienting of Attention*. New York: Oxford University Press.