Limitations of visuospatial attention (and how to circumvent them)

Dissertation zur Erlangung des Grades "Doktor der Naturwissenschaft"
im Fachbereich Humanwissenschaften der Universität Osnabrück

vorgelegt von

Basil Wahn

Osnabrück, November 17, 2016

Supervisor:
Prof. Dr. Peter König

Declaration of Authorship

I hereby certify that the work presented here is, to the best of my knowledge and belief, original and the result of my own investigations, except as acknowledged, and has not been submitted, either in part or whole, for a degree at this or any other university.

Osnabrück, November 17, 2016

Acknowledgements

I want to thank Peter König for his exceptional guidance and support. In addition, I want to thank all members of the Neurobiopsychology Lab for creating such a positive atmosphere to work in for the past three years.

Abstract

In daily life, humans are bombarded with visual input. Yet, their attentional capacities for processing this input are severely limited. Several studies, including my own, have investigated factors that influence these attentional limitations and have identified methods to circumvent them. In the present thesis, I provide a review of my own and others' findings. I first review studies that have demonstrated limitations of visuospatial attention and investigated physiological correlates of these limitations. I then turn to studies in multisensory research that have explored whether limitations in visuospatial attention can be circumvented by distributing information processing across several sensory modalities. Finally, I discuss research from the field of joint action that has investigated how limitations of visuospatial attention can be circumvented by distributing task demands across people and providing them with multisensory input. Based on the reviewed studies, I conclude that limitations of visuospatial attention can be circumvented by distributing attentional processing across sensory modalities when tasks involve spatial as well as object-based attentional processing. However, if only spatial attentional processing is required, limitations of visuospatial attention cannot be circumvented by distributing attentional processing. These findings from multisensory research are applicable to visuospatial tasks that are performed jointly by two individuals. That is, in a joint visuospatial task that does require object-based as well as spatial attentional processing, joint performance is facilitated when task demands are distributed across sensory modalities. Future research could further investigate how applying findings from multisensory research to joint action research may potentially facilitate joint performance. Generally, these findings are applicable to real-world scenarios such as aviation or car-driving to circumvent limitations of visuospatial attention.

Contents

1 Introduction

In everyday life, humans continuously process information from several sensory modalities. However, the amount of information humans can process is limited (Dux et al., 2006; Marois and Ivanoff, 2005). Due to limitations in processing, humans rely on attentional mechanisms to select only currently relevant sensory input while neglecting irrelevant sensory input (Chun et al., 2011; James, 1890). Researchers have explained these limitations in terms of a limited pool of attentional resources that can be depleted under high attentional demands (Lavie, 2005; Kahneman, 1973; Wickens, 2002). Moreover, several physiological substrates of attentional processing have been identified and studies have shown that the activity of these substrates correlates with the attentional demands (Alnæs et al., 2014; Drew et al., 2013; Jahn et al., 2012; Jovicich et al., 2001; Sternshein et al., 2011; Wahn et al., 2016a).

Regarding the type of attentional demands, a distinction in attention research is that between object-based attention and spatial attention (Fink et al., 1997; Serences et al., 2004; Soto and Blanco, 2004). Object-based attention refers to selectively attending to features of an object (e.g., attending to the color or shape of an object) whereas spatial attention refers to selectively attending to a location in space.

The present thesis will primarily focus on limitations of spatial attention in the visual sensory modality and on how these limitations can be circumvented. In the following, I first review findings about the limitations of spatial attention in the visual sensory modality with a focus on a particular visuospatial task (i.e., the multiple object tracking (MOT) task (Pylyshyn and Storm, 1988)). Moreover, I then briefly describe physiological correlates of attentional processing during visuospatial task performance. I then turn to review multisensory research that has investigated whether limitations in visuospatial attention can be circumvented by distributing information processing across several sensory modalities. Subsequently, I review research in which findings from multisensory research are applied to joint tasks (i.e., tasks that are performed jointly by two individuals). Finally, I conclude the thesis with future directions for research on how findings from multisensory research could be used to circumvent limitations of visuospatial attention in joint tasks.

2 Visuospatial attention: Limitations and physiological correlates

Limitations of visuospatial attention have been investigated in a wide variety of visuospatial tasks. One task that has been suggested to be ideal to investigate visuospatial attentional processing is the "Multiple Object Tracking" (MOT) task (Cavanagh and Alvarez, 2005; Pylyshyn and Storm, 1988; Yantis, 1992). In a MOT task, participants are required to track the movements of several target objects among randomly moving distractor objects on a computer screen (see Figure 2.1A, for a typical trial logic). The general finding across studies is that with an increasing number of to-be-tracked targets, performance in the MOT task systematically decreases (see Figure 2.1B), suggesting a limit of visuospatial attentional resources (Alvarez and Franconeri, 2007; Wahn et al., 2016a). Moreover, these capacity limitations are stable across several repetitions of the experiment on consecutive days (Wahn et al. (2016a), see Figure 2.1B and Appendix B, for the full paper) and over considerably longer periods of time (i.e., several years) (Alnæs et al., 2014).

The behavioral findings from the MOT task have been corroborated by studies that investigated the physiological correlates of attentional processing. A prominent physiological correlate of attentional processing that has been investigated for over a century are pupil sizes (Alnæs et al., 2014; Beatty, 1982; Kahneman and Beatty, 1966; Lisi et al., 2015; Mathôt et al., 2013, 2016; Naber et al., 2013; Heinrich, 1896; Hoeks and Levelt, 1993; Wierda et al., 2012). When people perform a task at varying difficulty levels, their pupil sizes systematically increase with increasing task difficulty. In the domain of attention research, increases in pupil sizes have been shown to be associated with increases in attentional load in recent studies that used the MOT task (Alnæs et al., 2014; Wahn et al., 2016a). Specifically, we have shown that when participants perform the MOT task at varying levels of attentional load, pupil sizes systematically

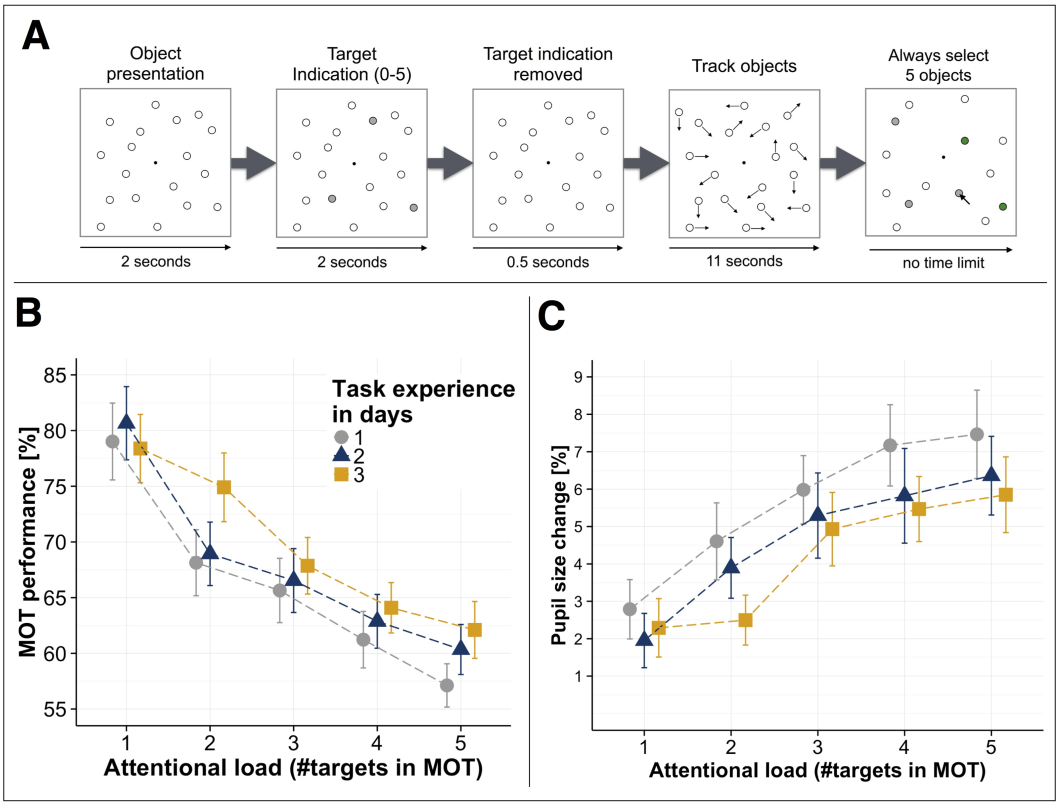

Figure 2.1: *A) Multiple object tracking (MOT) task trial logic. First, several stationary objects are shown on a computer screen. A subset of these objects is indicated as targets (here in gray). Then, the target indication is removed (i.e., targets become indistinguishable from the other objects) and all objects start moving randomly across the screen. After several seconds, the objects stop moving and participants are asked to select the previously indicated target objects. (B) MOT performance (i.e., percent correct of selected targets) as a function of attentional load (i.e., number of tracked objects) and days of measurement. (C) Pupil size increases relative to a passive viewing condition (i.e., tracking no targets) as a function of attentional load and days of measurement. Error bars in panels B and C are standard error of the mean. All figures have been adapted from Wahn et al. (2016a).*

increase with attentional load and these increases are consistently found for measurements on consecutive days (Wahn et al. (2016a), see Figure 2.1C, and Appendix B for the full paper). Apart from these studies investigating changes in pupil size, researchers also investigated physiological correlates of attentional processing using brain imaging techniques (i.e., fMRI) and electrophysiological measurement (i.e., EEG). Several fMRI studies have found parietal regions in the brain typically associated with attentional processing that were active when participants performed the MOT task (Alnæs et al., 2014; Howe et al., 2009; Jahn et al., 2012; Jovicich et al., 2001). Moreover, several EEG studies have identified neural correlates whose activity rises with increasing attentional load in the MOT task (Drew et al., 2013; Sternshein et al., 2011).

In sum, the MOT task has served to assess visuospatial attentional processing and the limitations of attentional resources in a number of studies (Alnæs et al., 2014; Alvarez and Franconeri, 2007; Wahn et al., 2016a). In particular, researchers have shown that attentional load in the MOT task (i.e., the number of tracked targets) correlates with physiological measures related to attentional processing (e.g., pupil sizes) (Alnæs et al., 2014; Wahn et al., 2016a). Overall, the MOT task is a suitable task to investigate resources of visuospatial attention. In the following, I discuss how the use of the MOT task has been extended to investigate spatial attentional resources across multiple sensory modalities.

3

Circumventing limitations of visuospatial attention

Are spatial attentional resources shared or distinct across sensory modalities?

A question that has been extensively investigated in multisensory research is whether there are distinct pools of attentional resources for each sensory modality or one shared pool of attentional resources for all sensory modalities. Studies have found empirical support for the hypothesis that there are distinct resources (Alais et al., 2006; Duncan et al., 1997; Finoia et al., 2015; Hein et al., 2006; Keitel et al., 2013; Larsen et al., 2003; Sinnett et al., 2006; Van der Burg et al., 2007; Potter et al., 1998; Soto-Faraco and Spence, 2002; Talsma et al., 2006) as well as for the hypothesis that there are shared resources (Arnell and Larson, 2002; Arnell and Jenkins, 2004; Jolicoeur, 1999; Macdonald and Lavie, 2011; Raveh and Lavie, 2015; Soto-Faraco et al., 2002). In principle, if there are separate pools of attentional resources, attentional limitations in one sensory modality can be circumvented by distributing attentional processing across several sensory modalities. Conversely, if there is only one shared pool of attentional resources for all sensory modalities, attentional limitations in one sensory modality cannot be circumvented by distributing attentional processing across several sensory modalities.

The question of whether there are shared or distinct attentional resources across the sensory modalities has often been investigated using dual task designs (Pashler, 1994). In a dual task design, participants perform two tasks separately ("single task condition") or at the same time ("dual task condition"). The extent to which attentional resources are shared for two tasks is assessed by comparing performance in the single task condition with performance in the dual task condition. If the attentional resources required for the two tasks are shared, task performance should decrease in the dual task condition relative to the single task condition. If attentional resources required for the two tasks are distinct, performance in the single and dual task conditions should not differ. In multisensory research, the two tasks in a dual task design are performed either in the same sensory modality or in different sensory modalities. The rationale of the design is that two tasks performed in the same sensory modality should always share attentional resources while two tasks performed in separate sensory modalities may or may not rely on shared attentional resources. That is, if attentional resources are distinct across sensory modalities, tasks performed in two separate sensory modalities should interfere less than tasks performed in the same sensory modality.

In the following, I will focus on research that has investigated how limitations in attentional resources for visuospatial attention can be circumvented by distributing information processing across sensory modalities using dual task designs.

Several researchers have suggested that a factor that influences the allocation of attentional resources across sensory modalities is the type of attentional processing that is required by specific tasks (Arrighi et al., 2011; Chan and Newell, 2008; Bonnel and Hafter, 1998; Wahn and König, 2016). That is, the allocation of attentional resources depends on whether tasks performed in separate sensory modalities require object-based attention or spatial attention. In recent studies (Arrighi et al., 2011; Wahn and König, 2015a,b), this task-dependency in attentional resource allocation has been tested in a dual task design involving a visuospatial task (i.e., a MOT task). In particular, the MOT task was performed either alone or in combination with a secondary task that was either performed in the visual, auditory, or tactile sensory modality. The secondary task either required object-based attention (i.e., the secondary task was a discrimination task) or spatial attention (i.e., the secondary task was a localization task). When participants performed the MOT task in combination with an object-based attention task in another sensory modality (i.e., an auditory pitch discrimination task), distinct attentional resources were found for the visual and auditory modalities (Arrighi et al., 2011). However, in our studies in which participants performed the MOT task in combination with either a tactile (Wahn and König, 2015b) or auditory spatial localization task (Wahn and König, 2015a), findings suggest that attentional resources are shared across the visual, tactile, and auditory sensory modalities. In particular, our results showed that regardless of whether two spatial attention tasks were performed in two separate sensory modalities or the same sensory modality (i.e., vision), tasks equally interfered with each other (see Figure 3.1A, see Appendices C & D for the full papers).

Further support for these conclusions was provided in another of our studies (Wahn and König, 2016) in which participants were required to perform a visual search task in combination with the same tactile localization task as used in an earlier study described above (Wahn and König, 2015b). In contrast to our earlier studies (Wahn and König, 2015a,b), this time we combined an object-based attention task (i.e., discriminating targets from distractors in a visual search task) with a spatial attention task (i.e., localizing spatial cues in a localization task). In particular, participants performed a visual search task either in combination with a visual or tactile localization task. In line with the findings above (Arrighi et al., 2011), participants performed the visual search task faster in combination with the tactile localization task than in combination with the visual localization task (see 3.1B, see Appendix E for the full paper). These findings suggest that attentional resources for the sensory modalities are distinct when tasks involve different types of attentional processing, i.e. object-based and spatial attentional processing.

In sum, the findings discussed above suggest that the allocation of attentional resources across sensory modalities (i.e., whether they are shared or distinct) depends on what type of attentional processing is required in a task. In particular, if tasks only require spatial attentional processing, evidence suggests that attentional resources are shared across sensory modalities (Wahn and König, 2015a,b). However, if tasks also require object-based attentional processing (e.g., discriminating pitches in an auditory discrimination task or targets from distractors in a visual search task), evidence suggests that attentional resources are distinct across the sensory modalities (Arrighi et al., 2011; Wahn and König, 2016). Importantly, limitations in visuospatial attention can be circumvented by distributing attentional processing across sensory modalities if tasks involve object-based as well as spatial attentional processing.

Does multisensory integration depend on visuospatial attentional resources?

Another process has been shown to result in facilitated information processing is the process of multisensory integration. Multisensory integration occurs when stimuli from multiple sensory modalities are integrated into one unitary percept (Ernst and Banks, 2002; Meredith and Stein, 1983; Stein and Stanford, 2008). This integration process depends on how information from several sensory modalities is received (i.e., whether sensory input from multiple sensory modalities coincide in time or space) and on whether input from multiple sensory modalities carries redundant information (Ernst and Banks, 2002; Helbig and Ernst, 2008; Meredith and Stein, 1983; Stein and Stanford, 2008; Wahn and König, 2016; van Atteveldt et al., 2014). The process of multisensory integration is associated with a variety of perceptual benefits such as a faster, more accurate and more reliable performance in comparison to the performance when humans receive sensory input from only one sensory modality (Ernst and Banks, 2002; Helbig and Ernst, 2008; Meredith and Stein, 1983; Stein and Stanford, 2008; Wahn and König, 2016). A question that has been frequently addressed in multisensory research is whether the process of multisensory integration is dependent on attentional resources (Alsius et al., 2005; Bertelson et al., 2000; Mozolic et al., 2008; Alsius et al., 2007, 2014; ten Oever et al., 2016; Talsma et al., 2010; Talsma, 2015; Misselhorn et al., 2015; Navarra et al., 2010). That is, whether diverting attention from stimuli that are typically integrated affects or even disrupts the integration process. Findings depend on a number of factors (for recent reviews, see: Chen and Spence (2016); Macaluso et al. (2016); ten Oever et al. (2016); Tang et al. (2016); van Atteveldt et al. (2014)). In the following, I will briefly discuss studies that have specifically focused on assessing whether diverting visuospatial attention affects the process of multisensory integration.

In two studies, we investigated how visuotactile and audiovisual integration in a localization task are affected by simultaneously performing a task requiring visuospatial attentional resources (Wahn and König, 2015a,b). Participants were required to localize audiovisual or visuotactile spatial cues while either performing the MOT task at the same time or not. Results showed that participants integrated the audiovisual as well as the visuotactile spatial cues regardless of whether the MOT task was performed at the same time or not. These findings suggest that the process of multisensory integration in a localization task is fairly robust against diverting visuospatial attention to a secondary task such that the benefits of multisensory integration (i.e., a faster, more accurate, & more reliable performance) were not reduced by diverting visuospatial attentional resources to a secondary task (see Appendices C & D, for the full papers). Other studies involving audiovisual speech stimuli however found that attentional load negatively affected the multisensory integration process (Alsius et al., 2005, 2007, 2014), suggesting that the type of stimuli (i.e., audiovisual speech or spatial stimuli) that are integrated across sensory modalities determine whether the multisensory integration process is susceptible to attentional load or not.

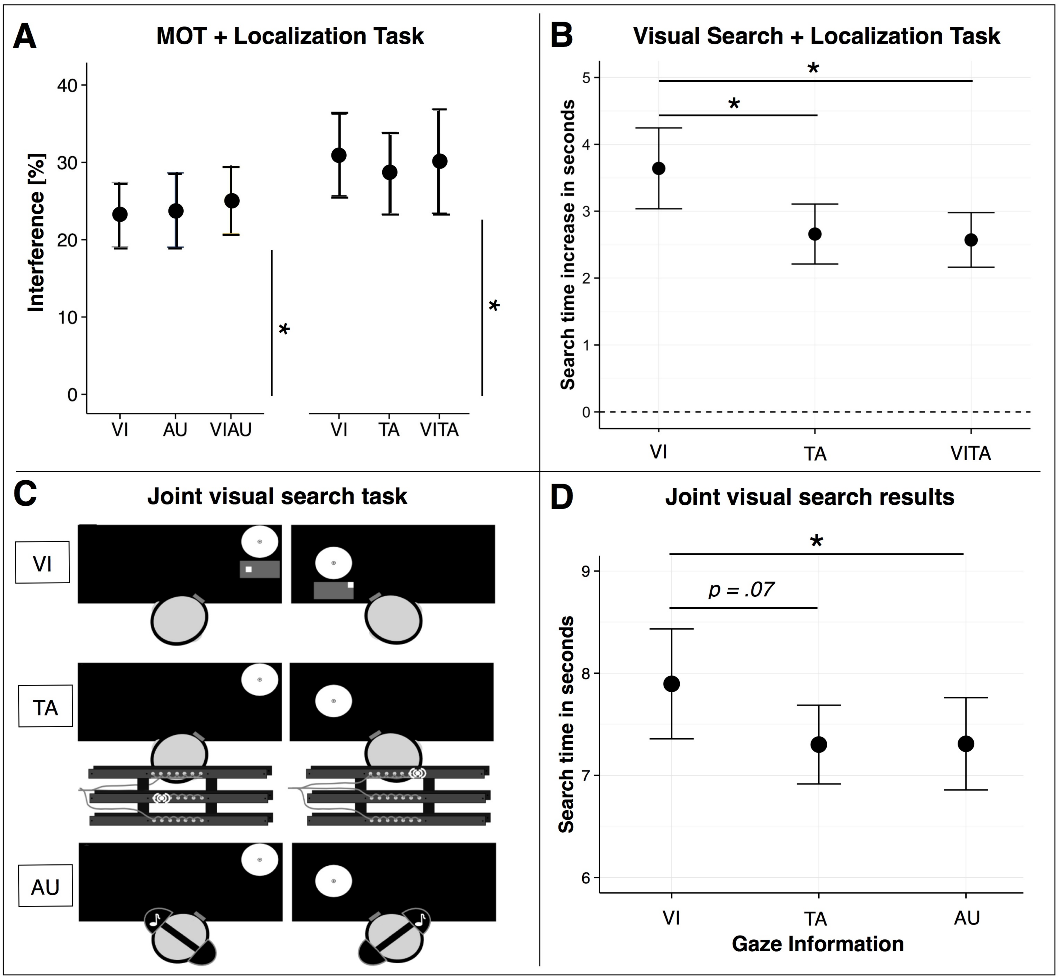

FIGURE 3.1: *(A) Dual task interference when participants perform the MOT task either in combination with a visual (VI), tactile (TA), audiovisual (VIAU), or visuotactile (VITA) localization task. Interference is measured as the reduction in performance between single and dual task conditions. In particular, the reduction in performance for both tasks (i.e., MOT and localization task) are combined by taking the Euclidean distance between single and dual task conditions (see Results section in Appendix D for more details), separately for each combination of tasks (MOT+VI, MOT+AU, MOT+TA, MOT+VIAU, MOT+VITA). (B) Search time increase relative to performing the visual search task alone when participants perform the same task either in combination with the VI, TA, or VITA localization task. (C) Joint visual search task conditions. Co-actors jointly searched for a target among distractors on two separate computer screens. A black mask was applied to the whole screen and only the currently viewed location was visible to the co-actors. Co-actors received the information about where their co-actor was looking either via a visual map (VI) that was displayed below their viewed location, via vibrations on a vibrotactile belt (TA), or via tones received through headphones (AU). (D) Joint visual search results. Search performance (i.e., time of the co-actor who found the target first) as a function of the sensory modality (VI, TA, or AU) in which the gaze information was received. Error bars in panels A,B, and D are standard error of the mean. * indicate significant comparisons with an alpha of .05. Figure A has been adapted from Wahn and König (2015a,b), B from Wahn and König (2016), and C and D from Wahn et al. (2015).*

4

Circumventing limitations of visuospatial attention in joint tasks

In previous sections, I have reviewed studies in which participants perform a task alone. However, in many situations in daily life, tasks are performed jointly by two or more humans with a shared goal (Sebanz et al., 2006). For instance, when two humans carry a table together (Sebanz et al., 2006), search for a friend in a crowd (Brennan et al., 2008), or play team sports such as basketball or soccer. In such joint tasks, humans often achieve higher performance than the better individual would achieve alone (i.e., a collective benefit) (Bahrami et al., 2010). Collective benefits have been investigated in several task domains such as visuomotor tasks (Ganesh et al., 2014; Knoblich and Jordan, 2003; Masumoto and Inui, 2013; Rigoli et al., 2015; Skewes et al., 2015; Wahn et al., 2016b), decision-making tasks (Bahrami et al., 2010, 2012a,b), and visuospatial tasks (Brennan et al., 2008; Brennan and Enns, 2015; Neider et al., 2010; Wahn et al., 2015).

Regarding visuospatial tasks, several studies have investigated joint performance in visual search tasks (Brennan et al., 2008; Brennan and Enns, 2015; Neider et al., 2010; Wahn et al., 2015). In particular, Brennan et al. (2008) investigated how performance in a joint visual search task depends on how information is exchanged between two co-actors. In a joint visual search task, two co-actors jointly search for a target stimulus among distractor stimuli. In Brennan et al. (2008), the two co-actors were either allowed to communicate verbally, or they received information about their co-actor's gaze location (indicated as a cursor on the screen), or they were allowed to communicate *and* received the gaze information. In an additional condition, no information was exchanged between co-actors. Brennan et al. (2008) found that co-actors performed the joint search the fastest and divided the task demands most effectively in the condition where they received only gaze information compared to the other conditions.

These findings suggest that co-actors in a joint visuospatial task benefit from receiving spatial and temporal information about the actions of their co-actor (e.g., a continuous display of the co-actor's gaze location).

Notably, the task demands in the joint visual search task as employed by Brennan et al. (2008) involve a combination of object-based attention (i.e., discriminate targets from distractors in the visual search task) and spatial attention (i.e., localize where the co-actor is looking using the gaze information). As reported above, findings in multisensory research suggest that limitations of visuospatial attention can be effectively circumvented by distributing information processing across sensory modalities if processing involves a combination of object-based attention and spatial attention (Arrighi et al., 2011; Wahn and König, 2016). In a recent study (Wahn et al., 2015, see Appendix F, for the full paper), we applied these findings from multisensory research to a joint visual search task setting similar to the one used by Brennan et al. (2008). In particular, we investigated whether joint visual search performance is faster when co-actors receive information about their co-actor's gaze location via the auditory or tactile sensory modality compared to when they receive this information via the visual modality (see 3.1C). We found that co-actors searched faster when they received the gaze information via the tactile or auditory sensory modalities than via the visual sensory modality (see 3.1D). These results suggest that findings from multisensory research mentioned above (Arrighi et al., 2011; Wahn and König, 2016) can be successfully applied to a joint visuospatial task.

5
Conclusions & future directions

The aim of the present thesis was to review recent studies investigating limitations in visuospatial attention. These studies have reliably found limitations of visuospatial attention and physiological correlates whose activity rises with increasing visuospatial attentional demands (Alnæs et al., 2014; Drew et al., 2013; Sternshein et al., 2011; Wahn et al., 2016a). Findings from multisensory research have demonstrated that such limitations of visuospatial attention can be circumvented by distributing information processing across sensory modalities (Arrighi et al., 2011; Wahn and König, 2015a,b, 2016). Specifically, it has been shown that limitations can be circumvented by distributing information across multiple sensory modalities only when tasks require spatial and object-based attention (Arrighi et al., 2011; Wahn and König, 2015a,b, 2016). These findings from multisensory research are applicable to joint settings where two individuals collaboratively perform a visuospatial task. If a joint visuospatial task requires object-based as well as spatial attentional processing, joint performance is facilitated when information processing is distributed across sensory modalities (Wahn et al., 2015).

Apart from the study above (Wahn et al., 2015), other studies on joint action have investigated how the use of multisensory stimuli (e.g., visual and auditory) can serve to facilitate joint performance (Knoblich and Jordan, 2003) and how the process of multisensory integration is affected by social settings (Heed et al., 2010). However, these studies have not investigated how distributing information processing across sensory modalities potentially could facilitate joint performance. We suggest that future studies could further investigate to what extent findings from multisensory research are applicable to joint tasks.

Based on findings from multisensory research, attentional limitations may be circumvented in every joint task that involves a combination of object-based and spatial attentional processing in the visual sensory modality. In such tasks, part of the burden on visual information processing could be relieved by providing information in another sensory modality, thereby possibly facilitating joint performance. For instance, in a joint visuomotor task that we investigated (Wahn et al., 2016b, see Appendix G, for the full paper), co-actors processed visuospatial information related to performing the visuomotor task. In a future study, while performing the visuomotor task, task-relevant information requiring object-based attentional processing could be exchanged between co-actors via a different sensory modality than vision, thereby potentially facilitating joint performance. Relatedly, research on joint visuospatial tasks has shown that successful joint action does rely on an effective exchange of spatial information between co-actors (Brennan et al., 2008; Neider et al., 2010; Wahn et al., 2015). Future research may investigate whether the effectiveness of the information exchange could be further improved by providing redundant information via several sensory modalities, thereby making use of the benefits of multisensory integration (i.e., a faster, more accurate and more reliable performance).

The possibility to circumvent limitations of visuospatial attention is also relevant for many real-world tasks that require visuospatial attention such as car-driving (Spence and Read, 2003; Kunar et al., 2008; Spence and Ho, 2012), air-traffic control (Giraudet et al., 2014), aviation (Nikolic et al., 1998; Sklar and Sarter, 1999), or navigation (Nagel et al., 2005; Kaspar et al., 2014). In such scenarios, limitations of visuospatial attention could be effectively circumvented by distributing attentional processing across sensory modalities.

Finally, future studies could test to what extent the conclusions put forward in the present thesis hold for limitations in spatial attention in other sensory modalities than vision, such as audition or touch, i.e., whether limitations of spatial attention in audition and touch could also be circumvented by distributing attentional processing across sensory modalities.

A

Curriculum Vitae

1 Peer-reviewed publications

Publications that are part of the thesis are marked with an *

2017

Wahn, B., & König, P. (2017). Is Attentional Resource Allocation Across Sensory Modalities Task-Dependent? *Advances in Cognitive Psychology*, 13, 83-96, doi:10.5709/acp-0209-2

Wahn, B., Murali, S., Sinnett, S., & König, P. (2017). Auditory stimulus detection partially depends on visuospatial attentional resources. *i-Perception*, 1–18, doi: 10.1177/2041669516688026

Vesper, C., Abramova, E., Bütepage, J., Ciardo, F., Crossey, B., Effenberg, A., Hristova, D., Karlinsky, A., McEllin, L., Nijssen, S., Schmitz, L., & **Wahn, B.** (2017). Joint Action: Mental Representations, Shared Information and General Mechanisms for Coordinating with Others. *Frontiers in Psychology*, 7, 2039. doi: 10.3389/fpsyg.2016.02039

2016

***Wahn, B.**, Ferris, D.P., Hairston, W. D., & König, P. (2016). Pupil sizes scale with attentional load and task experience in a multiple object tracking task. PloS ONE, *11*(12), e0168087. doi: 10.1371/journal.pone.0168087

König, S. U., Schumann, F., Keyser, J., Goeke, C., Krause, C., Wache, S., Lytochkin, A., Ebert, M., Brunsch, V., **Wahn, B.**, Kaspar, K., Nagel, S. K., Meilinger, T., Bülthoff, H., Wolbers, T., Büchel, C., & König, P. (2016). Learning New Sensorimotor Contingencies: Effects of Long-Term Use of Sensory Augmentation on the Brain and Conscious Perception. PLoS ONE, *11*(12), e0166647. doi: 10.1371/journal.pone.0166647

***Wahn, B.**, Schmitz, L., König P.$^{+}$, & Knoblich, G.$^{+}$ (2016) Benefiting from being alike: Interindividual skill differences predict collective benefit in joint object control ($^{+}$shared senior authorship). In A. Papafragou, D. Grodner, D. Mirman, & J.C. Trueswell (Eds.) *Proceedings of the 38th Annual Conference of the Cognitive Science Society*, 2747 - 2752. Austin, TX: Cognitive Science Society.

***Wahn, B.** & König, P. (2016). Attentional resource allocation in visuotactile processing depends on the task, but optimal visuotactile integration does not depend on attentional resources. *Frontiers in Integrative Neuroscience*. 10(13). http://dx.doi.org/10.3389/fnint.2016.00013

2015

***Wahn, B.**, Schwandt, J., Krüger, M., Crafa, D., Nunnendorf, V., & König P. (2015) Multisensory teamwork: Using a tactile or an auditory display to exchange gaze information improves performance in joint visual search. *Ergonomics*. 59(6). 781-795. http://dx.doi.org/10.1080/00140139.2015.1099742

***Wahn, B.** & König, P. (2015). Audition and vision share spatial attentional resources, yet attentional load does not disrupt audiovisual integration. *Frontiers in Psychology*. 6(1084). http://dx.doi.org/10.3389/fpsyg.2015.01084

***Wahn, B.** & König, P. (2015). Vision and haptics share spatial attentional resources and visuotactile integration is not affected by high attentional load. *Multisensory Research*. 28 (3-4), 371-392. http://dx.doi.org/10.1163/22134808-00002482

2 Talks

2016

13th Biannual Conference of the German Society for Cognitive Science
Wahn, B., Murali, S., & König, P. (2016). Auditory stimulus detection partially depends on visuospatial attentional resources.

38th Annual Conference of the Cognitive Science Society
Wahn, B., Schmitz, L., König P.$^{+}$, & Knoblich, G.$^{+}$ (2016) Benefiting from being alike: Interindividual skill differences predict collective benefit in joint object control ($^{+}$shared senior authorship)

Northwest Cognition and Memory (NOWCAM)
Wahn, B., Milani, S., König, P. & Kingstone, A. (2016). Humans' willingness to co-operate with a computer partner depends on feedback about the team's performance

2015

European Conference on Visual Perception (ECVP)
Wahn, B., & König, P. (2015). Vision shares spatial attentional resources with haptics and audition, yet attentional load does not disrupt visuotactile or audiovisual integration. *Perception*, 44, 373–374

3 Poster presentations

2016

38th Annual Conference of the Cognitive Science Society
Wahn, B., & König, P. (2016). Attentional Resource Allocation in Multisensory Processing is Task-dependent

European Conference on Visual Perception (ECVP)
Wahn, B., Kingstone, A. & König, P. (2016). Collaborative multiple object tracking:

How many objects can you track and which ones did you pick?

Spatial Cognition
Wahn, B., & König, P. (2016). How effective is an auditory or a tactile display to circumvent visuospatial processing limitations in tasks performed alone or in a group?

2015

Joint Action Meeting (JAM)
Schmitz, L.*, **Wahn, B.***, Knoblich, G.+, & König P.+ (2015) Let's move it together: The costs and benefits of shared action control. (*shared first authorship, +shared senior authorship)

International Multisensory Research Forum (IMRF)
Wahn, B., & König, P. (*2015*). Visual and tactile attentional resources are shared in sustained spatial tasks and high attentional load does not disrupt visuotactile integration.

2014

Interdisciplinary College Günne
Wahn, B., Schwandt J., Krüger, M., Crafa, D., Nunnendorf, V., & König P. (2014). Sensing Where You Search: Attentional Benefits in a Collaborative Visual Search Task Through Tactile Transmission of 2D Spatial Information

Synaesthesia in Perspective: Development, Networks, and Multisensory Processing
Wahn, B., Schwandt J., Krüger, M., Crafa, D., Nunnendorf, V., & König P. (2014). Sensing Where You Search: Attentional Benefits in a Collaborative Visual Search Task Through Tactile Transmission of 2D Spatial Information

2013

European Conference on Visual Perception (ECVP)
Kietzmann, T. C., **Wahn, B.**, König, P., & Tong, F. (2013). Face selective areas in the human ventral stream exhibit a preference for 3/4 views in the fovea and periphery. *Perception*, 42, 54.

Osnabrück Computational Alliance Meeting (OCCAM)

Wahn, B., Schwandt J., Krüger, M., Crafa, D., Nunnendorf, V., & König P. (2013). Attentional Benefits in a Visual Joint Search Task Through Tactile and Auditory Transmission of Two-Dimensional Spatial Information

4 f1000 Recommendations

König, P. & **Wahn, B.**: F1000Prime Recommendation of [Cohen MA et al., Proc Natl Acad Sci USA 2014, 111(24):8955-60]. In F1000Prime, 13 Apr 2016;
DOI: 10.3410/f.718431295.793516535.

König, P. & **Wahn, B.**: F1000Prime Recommendation of [Alnæs D et al., J Vis 2014, 14(4)]. In F1000Prime, 17 Dec 2015; DOI:10.3410/f.718336015.793512341.

König, P. & **Wahn, B.**: F1000Prime Recommendation of [Talsma D, Front Integr Neurosci 2015, 9:19]. In F1000Prime, 08 Oct 2015; DOI:10.3410/f.725431254.793510169.

5 Supervision of Bachelor/Master theses and study projects

"Cortical mechanisms of joint action" (*completed*). Studyproject by Anete Aumeistere, Chiara Carrera, Artur Czeszumski, Ernesto Andres Lopez Montecinos, & Ann Xavier

"Attentional resources for audition and vision depend on the type of task and audiovisual integration is not affected by attention load" (*completed*). MSc by Supriya Murali

"Error processing and adaptive behavior in different social contexts" (*ongoing*). MSc by Chiara Carrera & Artur Czeszumski

"Joint Loss" (*ongoing*). MSc by Max Räucker

"The neurophysiology of joint action" (*ongoing*). Studyproject by Kristina Baumgart, Petr Byvshev, Alexa-Nicole Sliby, Raul Sulaimanov, Andreas Strube, & Paola

Ramirez Suarez

“Mechanisms of joint attention” (*ongoing*). Studyproject by Dominic Akwesi Agyei, Obioma Chimezie Amaefule, Mohammadreza Baghery, Shadi Derakhshan, Regina Gerber, Greta Häberle, Mahsa Khaleghi, Gürhan Konya, & Steven Osborne

Teaching experience

October 2016 – March 2017 Lecturer for Seminar: “Advanced Topics in Action & Cognition 17a”

October 2016 – March 2017 Lecturer for Study Project: “The neurophysiology of joint action (Part I)”

April 2016 – July 2016 Lecturer for Study Project: “Cortical mechanisms of joint action (Part II)”

April 2016 – July 2016 Teaching assistant for Lecture: “Action & Cognition II”

October 2015 – February 2016: Lecturer for Study Project: “Cortical mechanisms of joint action (Part I)”

October 2015 – February 2016: Co-organizer for Colloquium: “Colloquium of the Institute of Cognitive Science”

April 2015 – July 2015: Lecturer for Seminar: “Doing Bayesian Data Analysis": together with Dr. Tim C. Kietzmann

October 2012 – February 2013: Teaching assistant for “Multivariate Statistics"

October 2012 – February 2013: Teaching assistant for “Test, Scale & Decide"

October 2012 – February 2013: Teaching assistant for “Action & Cognition I"

April 2012 – July 2012: Teaching assistant for “Action & Cognition II"

October 2011 – February 2012: Teaching assistant for "Statistics I"

Working experience

October 2013 – present: Research assistant (Neurobiopsychology Lab, Institute of Cognitive Science, University of Osnabrück)

June 2013 – July 2016: Statistical consultant (Psychology Department, University of Osnabrück)

B

"Pupil sizes scale with attentional load and task experience in a multiple object tracking task"

The fulltext for this paper can be found here: Wahn, B., Ferris, D. P., Hairston, W. D., & König, P. (2016). Pupil sizes scale with attentional load and task experience in a multiple object tracking task. PLoS ONE, *11*(12), e0168087. http://dx.doi.org/10.1371/journal.pone.0168087

Acknowledgments: We want to thank Lisa Steinmetz, Artur Czeszumski, and Ashima Keshava for their help with the data collection.

Funding: We gratefully acknowledge the support by H2020 – H2020-FETPROACT-2014 641321 – socSMCs (for BW), ERC-2010-AdG #269716 – MULTISENSE (for PK), and the Cognition and Neuroergonomics Collaborative Technology Alliance ARL W91 1NF-10-2-0022 (for DPF and WDH)

C

“Vision and haptics share spatial attentional resources and visuotactile integration is not affected by high attentional load”

The fulltext for this paper can be found here: Wahn, B. & König, P. (2015). Vision and Haptics Share Spatial Attentional Resources and Visuotactile Integration Is Not Affected by High Attentional Load. *Multisensory Research*, 28(3-4), 371-392. http://dx.doi.org/10.1163/22134808-00002482

Acknowledgments: We want to thank Jessika Schwandt, Vanessa Nunnendorf and Alexandra Bidler for their help in constructing the vibrotactile belt. A special thanks goes to Laura Schmitz for her valuable feedback on this manuscript.

Funding: We gratefully acknowledge the support by H2020 – H2020-FETPROACT-2014 641321 – socSMCs (for BW), FP7-ICT-270212 – eSMCs (for PK and BW) and ERC- 2010-AdG #269716 – MULTISENSE (for PK).

D

"Audition and vision share spatial attentional resources, yet attentional load does not disrupt audiovisual integration"

The fulltext for this paper can be found here: Wahn, B. & König, P. (2015). Audition and vision share spatial attentional resources, yet attentional load does not disrupt audiovisual integration. *Frontiers in Psychology*, 6:1084.

http://dx.doi.org/10.3389/fpsyg.2015.01084

Acknowledgments: As this study is a close follow-up study to our previous study (Wahn and König, 2015b), in which tactile spatial cues instead of auditory spatial cues were used, we like to acknowledge that content which is analogous to both studies was reproduced from the previous article with permission of the publishing company Koninklijke Brill NV. We want to thank Supriya Murali and Anette Aumeistere for their help in creating the auditory stimuli and collecting the data.

Funding: We gratefully acknowledge the support by H2020 – H2020-FETPROACT-2014 641321 – socSMCs (for BW), FP7-ICT-270212 – eSMCs (for PK and BW) and ERC- 2010-AdG #269716 – MULTISENSE (for PK).

E

"Attentional resource allocation in visuotactile processing depends on the task, but optimal visuotactile integration does not depend on attentional resources"

The fulltext for this paper can be found here: Wahn, B. & König, P. (2016). Attentional resource allocation in visuotactile processing depends on the task, but optimal visuotactile integration does not depend on attentional resources. *Frontiers in Integrative Neuroscience*, 10:13. http://dx.doi.org/10.3389/fnint.2016.00013

Acknowledgments: As this study is a close follow-up to our previous study (Wahn and König, 2015b), we like to acknowledge that content which is analogous to both studies was reproduced from the previous article with permission of the publishing company Koninklijke Brill NV.

Funding:: We gratefully acknowledge the support by H2020 – H2020-FETPROACT-2014 641321 – socSMCs (for BW) and ERC-2010-AdG #269716 – MULTISENSE (for PK).

F

"Multisensory teamwork: Using a tactile or an auditory display to exchange gaze information improves performance in joint visual search"

The fulltext for this paper can be found here: Wahn, B., Schwandt, J., Krüger, M., Crafa, D., Nunnendorf, V., & König P. (2015). Multisensory teamwork: Using a tactile or an auditory display to exchange gaze information improves performance in joint visual search. *Ergonomics*, 59(6). 781-795.

http://dx.doi.org/10.1080/00140139.2015.1099742

Acknowledgments: We want to thank Alexandra Bidler, Anna-Lena Lumma, Aleksey Lytochkin, Vikash Murthy Peesapati, Ricardo Ramos Gameiro and Niklas Wilming for their help in designing and conducting this study. We also like to thank Laura Schmitz for her valuable feedback on the manuscript.

Funding: This work was supported by the Cognition and Neuroergonomics / Collaborative Technology Alliance under Grant #W911NF-10-2-0022, ERC-2010-AdG under Grant #269716 – "MULTISENSE" and by H2020 under Grant H2020-FETPROACT-2014 641321 – "socSMCs".

G

"Benefiting from Being Alike: Interindividual Skill Differences Predict Collective Benefit in Joint Object Control"

The fulltext for the paper can be found here: Wahn, B., Schmitz, L., König P.$^{+}$, & Knoblich, G.$^{+}$ (2016). Benefiting from being alike: Interindividual skill differences predict collective benefit in joint object control ($^{+}$shared senior authorship). In A. Papafragou, D. Grodner, D. Mirman, & J.C. Trueswell (Eds.) *Proceedings of the 38th Annual Conference of the Cognitive Science Society*, 2747 – 2752, Austin, TX: Cognitive Science Society. https://mindmodeling.org/cogsci2016/papers/0473/paper0473.pdf

Funding: This research was supported by H2020–H2020-FETPROACT-2014641321–socSMCs (for BW & PK) and by the European Research Council under the European Union's Seventh Framework Program (FP7/2007-2013) / ERC grant agreement n° [609819], SOMICS, and by ERC grant agreement n°616072, JAXPERTISE (for LS & GK).

Bibliography

Alais, D., Morrone, C., and Burr, D. (2006). Separate attentional resources for vision and audition. *Proceedings of the Royal Society B: Biological Sciences*, 273(1592):1339–1345.

Alnæs, D., Sneve, M. H., Espeseth, T., Endestad, T., van de Pavert, S. H. P., and Laeng, B. (2014). Pupil size signals mental effort deployed during multiple object tracking and predicts brain activity in the dorsal attention network and the locus coeruleus. *Journal of Vision*, 14(4):1.

Alsius, A., Möttönen, R., Sams, M. E., Soto-Faraco, S., and Tiippana, K. (2014). Effect of attentional load on audiovisual speech perception: evidence from erps. *Frontiers in Psychology*, 5.

Alsius, A., Navarra, J., Campbell, R., and Soto-Faraco, S. (2005). Audiovisual integration of speech falters under high attention demands. *Current Biology*, 15(9):839–843.

Alsius, A., Navarra, J., and Soto-Faraco, S. (2007). Attention to touch weakens audiovisual speech integration. *Experimental Brain Research*, 183(3):399–404.

Alvarez, G. A. and Franconeri, S. L. (2007). How many objects can you track?: Evidence for a resource-limited attentive tracking mechanism. *Journal of Vision*, 7(13):14.

Arnell, K. M. and Jenkins, R. (2004). Revisiting within-modality and cross-modality attentional blinks: Effects of target–distractor similarity. *Perception & Psychophysics*, 66:1147–1161.

Arnell, K. M. and Larson, J. M. (2002). Cross-modality attentional blinks without preparatory task-set switching. *Psychonomic Bulletin & Review*, 9:497–506.

Arrighi, R., Lunardi, R., and Burr, D. (2011). Vision and audition do not share attentional resources in sustained tasks. *Frontiers in Psychology*, 2.

Bahrami, B., Olsen, K., Bang, D., Roepstorff, A., Rees, G., and Frith, C. (2012a). Together, slowly but surely: the role of social interaction and feedback on the build-up of benefit in collective decision-making. *Journal of Experimental Psychology: Human Perception and Performance*, 38(1):3–8.

Bahrami, B., Olsen, K., Bang, D., Roepstorff, A., Rees, G., and Frith, C. (2012b). What failure in collective decision-making tells us about metacognition. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 367(1594):1350–1365.

Bahrami, B., Olsen, K., Latham, P. E., Roepstorff, A., Rees, G., and Frith, C. D. (2010). Optimally interacting minds. *Science*, 329(5995):1081–1085.

Beatty, J. (1982). Task-evoked pupillary responses, processing load, and the structure of processing resources. *Psychological Bulletin*, 91(2):276.

Bertelson, P., Vroomen, J., De Gelder, B., and Driver, J. (2000). The ventriloquist effect does not depend on the direction of deliberate visual attention. *Perception & Psychophysics*, 62(2):321–332.

Bonnel, A.-M. and Hafter, E. R. (1998). Divided attention between simultaneous auditory and visual signals. *Perception & Psychophysics*, 60(2):179–190.

Brennan, A. A. and Enns, J. T. (2015). When two heads are better than one: Interactive versus independent benefits of collaborative cognition. *Psychonomic Bulletin & Review*, 22(4):1076–1082.

Brennan, S. E., Chen, X., Dickinson, C. A., Neider, M. B., and Zelinsky, G. J. (2008). Coordinating cognition: The costs and benefits of shared gaze during collaborative search. *Cognition*, 106:1465–1477.

Cavanagh, P. and Alvarez, G. A. (2005). Tracking multiple targets with multifocal attention. *Trends in Cognitive Sciences*, 9(7):349–354.

Chan, J. S. and Newell, F. N. (2008). Behavioral evidence for task-dependent "what" versus "where" processing within and across modalities. *Perception & Psychophysics*, 70(1):36–49.

Chen, Y.-C. and Spence, C. (2016). Hemispheric asymmetry: Looking for a novel signature of the modulation of spatial attention in multisensory processing. *Psychonomic Bulletin & Review*, pages 1–18.

Chun, M. M., Golomb, J. D., and Turk-Browne, N. B. (2011). A taxonomy of external and internal attention. *Annual Review of Psychology*, 62:73–101.

Drew, T., Horowitz, T. S., and Vogel, E. K. (2013). Swapping or dropping? electrophysiological measures of difficulty during multiple object tracking. *Cognition*, 126(2):213–223.

Duncan, J., Martens, S., and Ward, R. (1997). Restricted attentional capacity within but not between sensory modalities. *Nature*, 397:808–810.

Dux, P. E., Ivanoff, J., Asplund, C. L., and Marois, R. (2006). Isolation of a central bottleneck of information processing with time-resolved fmri. *Neuron*, 52(6):1109–1120.

Ernst, M. O. and Banks, M. S. (2002). Humans integrate visual and haptic information in a statistically optimal fashion. *Nature*, 415(6870):429–433.

Fink, G., Dolan, R., Halligan, P., Marshall, J., and Frith, C. (1997). Space-based and object-based visual attention: shared and specific neural domains. *Brain*, 120(11):2013–2028.

Finoia, P., Mitchell, D. J., Hauk, O., Beste, C., Pizzella, V., and Duncan, J. (2015). Concurrent brain responses to separate auditory and visual targets. *Journal of Neurophysiology*, 114(2):1239–1247.

Ganesh, G., Takagi, A., Osu, R., Yoshioka, T., Kawato, M., and Burdet, E. (2014). Two is better than one: Physical interactions improve motor performance in humans. *Scientific Reports*, 4.

Giraudet, L., Berenger, M., Imbert, J.-P., Tremblay, S., and Causse, M. (2014). Inattentional deafness in simulated air traffic control tasks: A behavioral and p300 analysis.

Heed, T., Habets, B., Sebanz, N., and Knoblich, G. (2010). Others' actions reduce crossmodal integration in peripersonal space. *Current Biology*, 20(15):1345–1349.

Hein, G., Parr, A., and Duncan, J. (2006). Within-modality and cross-modality attentional blinks in a simple discrimination task. *Perception & Psychophysics*, 68:54–61.

Heinrich, W. (1896). Die aufmerksamkeit und die funktion der sinnesorgane. *Zeitschrift für Psychologie und Physiologie der Sinnesorgane*, pages 342–388.

Helbig, H. B. and Ernst, M. O. (2008). Visual-haptic cue weighting is independent of modality-specific attention. *Journal of Vision*, 8(1):21.

Hoeks, B. and Levelt, W. J. (1993). Pupillary dilation as a measure of attention: A quantitative system analysis. *Behavior Research Methods, Instruments, & Computers*, 25(1):16–26.

Howe, P. D., Horowitz, T. S., Morocz, I. A., Wolfe, J., and Livingstone, M. S. (2009). Using fmri to distinguish components of the multiple object tracking task. *Journal of Vision*, 9(4):10–10.

Jahn, G., Wendt, J., Lotze, M., Papenmeier, F., and Huff, M. (2012). Brain activation during spatial updating and attentive tracking of moving targets. *Brain and Cognition*, 78(2):105–113.

James, W. (1890). The principles of psychology. *Harvard UP, Cambridge, MA*.

Jolicoeur, P. (1999). Restricted attentional capacity between sensory modalities. *Psychonomic Bulletin & Review*, 6:87–92.

Jovicich, J., Peters, R. J., Koch, C., Braun, J., Chang, L., and Ernst, T. (2001). Brain areas specific for attentional load in a motion-tracking task. *Journal of Cognitive Neuroscience*, 13(8):1048–1058.

Kahneman, D. (1973). *Attention and effort*. Citeseer.

Kahneman, D. and Beatty, J. (1966). Pupil diameter and load on memory. *Science*, 154(3756):1583–1585.

Kaspar, K., König, S., Schwandt, J., and König, P. (2014). The experience of new sensorimotor contingencies by sensory augmentation. *Consciousness and Cognition*, 28:47–63.

Keitel, C., Maess, B., Schröger, E., and Müller, M. M. (2013). Early visual and auditory processing rely on modality-specific attentional resources. *Neuroimage*, 70:240–249.

Knoblich, G. and Jordan, J. S. (2003). Action coordination in groups and individuals: learning anticipatory control. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 29(5):1006–1016.

Kunar, M. A., Carter, R., Cohen, M., and Horowitz, T. S. (2008). Telephone conversation impairs sustained visual attention via a central bottleneck. *Psychonomic Bulletin & Review*, 15(6):1135–1140.

Larsen, A., McIlhagga, W., Baert, J., and Bundesen, C. (2003). Seeing or hearing? perceptual independence, modality confusions, and crossmodal congruity effects with focused and divided attention. *Perception & Psychophysics*, 65(4):568–574.

Lavie, N. (2005). Distracted and confused?: Selective attention under load. *Trends in Cognitive Sciences*, 9(2):75–82.

Lisi, M., Bonato, M., and Zorzi, M. (2015). Pupil dilation reveals top–down attentional load during spatial monitoring. *Biological Psychology*, 112:39–45.

Macaluso, E., Noppeney, U., Talsma, D., Vercillo, T., Hartcher-O'Brien, J., and Adam, R. (2016). The curious incident of attention in multisensory integration: Bottom-up vs. top-down. *Multisensory Research*, 29(6-7):557–583.

Macdonald, J. S. and Lavie, N. (2011). Visual perceptual load induces inattentional deafness. *Attention, Perception, & Psychophysics*, 73(6):1780–1789.

Marois, R. and Ivanoff, J. (2005). Capacity limits of information processing in the brain. *Trends in Cognitive Sciences*, 9(6):296–305.

Masumoto, J. and Inui, N. (2013). Two heads are better than one: both complementary and synchronous strategies facilitate joint action. *Journal of Neurophysiology*, 109(5):1307–1314.

Mathôt, S., Melmi, J.-B., van der Linden, L., and Van der Stigchel, S. (2016). The mind-writing pupil: A human-computer interface based on decoding of covert attention through pupillometry. *PLoS ONE*, 11(2):e0148805.

Mathôt, S., Van der Linden, L., Grainger, J., and Vitu, F. (2013). The pupillary light response reveals the focus of covert visual attention. *PLoS ONE*, 8(10):e78168.

Meredith, M. A. and Stein, B. E. (1983). Interactions among converging sensory inputs in the superior colliculus. *Science*, 221(4608):389–391.

Misselhorn, J., Daume, J., Engel, A. K., and Friese, U. (2015). A matter of attention: Crossmodal congruence enhances and impairs performance in a novel trimodal matching paradigm. *Neuropsychologia*.

Mozolic, J. L., Hugenschmidt, C. E., Peiffer, A. M., and Laurienti, P. J. (2008). Modality-specific selective attention attenuates multisensory integration. *Experimental brain research*, 184(1):39–52.

Naber, M., Alvarez, G. A., and Nakayama, K. (2013). Tracking the allocation of attention using human pupillary oscillations. *Frontiers in Psychology*, 4.

Nagel, S. K., Carl, C., Kringe, T., Märtin, R., and König, P. (2005). Beyond sensory substitution—learning the sixth sense. *Journal of Neural Engineering*, 2:R13–R26.

Navarra, J., Alsius, A., Soto-Faraco, S., and Spence, C. (2010). Assessing the role of attention in the audiovisual integration of speech. *Information Fusion*, 11(1):4–11.

Neider, M. B., Chen, X., Dickinson, C. A., Brennan, S. E., and Zelinsky, G. J. (2010). Coordinating spatial referencing using shared gaze. *Psychonomic Bulletin & Review*, 17:718–724.

Nikolic, M. I., Sklar, A. E., and Sarter, N. B. (1998). Multisensory feedback in support of pilot-automation coordination: the case of uncommanded mode transitions. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, volume 42, pages 239–243. SAGE Publications.

Pashler, H. (1994). Dual-task interference in simple tasks: data and theory. *Psychological Bulletin*, 116(2):220.

Potter, M. C., Chun, M. M., Banks, B. S., and Muckenhoupt, M. (1998). Two attentional deficits in serial target search: The visual attentional blink and an amodal task-switch deficit. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 24:979–992.

Pylyshyn, Z. W. and Storm, R. W. (1988). Tracking multiple independent targets: Evidence for a parallel tracking mechanism. *Spatial Vision*, 3(3):179–197.

Raveh, D. and Lavie, N. (2015). Load-induced inattentional deafness. *Attention, Perception, & Psychophysics*, 77(2):483–492.

Rigoli, L., Romero, V., Shockley, K., Funke, G. J., Strang, A. J., and Richardson, M. J. (2015). Effects of complementary control on the coordination dynamics of joint-action. *Proceedings of the 37th Annual Conference of the Cognitive Science Society*, pages 1997–2002.

Sebanz, N., Bekkering, H., and Knoblich, G. (2006). Joint action: bodies and minds moving together. *Trends in Cognitive Sciences*, 10(2):70–76.

Serences, J. T., Schwarzbach, J., Courtney, S. M., Golay, X., and Yantis, S. (2004). Control of object-based attention in human cortex. *Cerebral Cortex*, 14(12):1346–1357.

Sinnett, S., Costa, A., and Soto-Faraco, S. (2006). Manipulating inattentional blindness within and across sensory modalities. *The Quarterly Journal of Experimental Psychology*, 59(8):1425–1442.

Skewes, J. C., Skewes, L., Michael, J., and Konvalinka, I. (2015). Synchronised and complementary coordination mechanisms in an asymmetric joint aiming task. *Experimental Brain Research*, 233(2):551–565.

Sklar, A. E. and Sarter, N. B. (1999). Good vibrations: Tactile feedback in support of attention allocation and human-automation coordination in event- driven domains. *Human Factors*, 41:543–552.

Soto, D. and Blanco, M. J. (2004). Spatial attention and object-based attention: a comparison within a single task. *Vision Research*, 44(1):69–81.

Soto-Faraco, S. and Spence, C. (2002). Modality-specific auditory and visual temporal processing deficits. *The Quarterly Journal of Experimental Psychology*, 55:23–40.

Soto-Faraco, S., Spence, C., Fairbank, K., Kingstone, A., Hillstrom, A. P., and Shapiro, K. (2002). A crossmodal attentional blink between vision and touch. *Psychonomic Bulletin & Review*, 9(4):731–738.

Spence, C. and Ho, C. (2012). *The multisensory driver: Implications for ergonomic car interface design*. Ashgate Publishing, Ltd.

Spence, C. and Read, L. (2003). Speech shadowing while driving on the difficulty of splitting attention between eye and ear. *Psychological Science*, 14(3):251–256.

Stein, B. E. and Stanford, T. R. (2008). Multisensory integration: current issues from the perspective of the single neuron. *Nature Reviews Neuroscience*, 9(4):255–266.

Sternshein, H., Agam, Y., and Sekuler, R. (2011). Eeg correlates of attentional load during multiple object tracking. *PLoS ONE*, 6(7):e22660.

Talsma, D. (2015). Predictive coding and multisensory integration: an attentional account of the multisensory mind. *Frontiers in Integrative Neuroscience*, 9.

Talsma, D., Doty, T. J., Strowd, R., and Woldorff, M. G. (2006). Attentional capacity for processing concurrent stimuli is larger across sensory modalities than within a modality. *Psychophysiology*, 43(6):541–549.

Talsma, D., Senkowski, D., Soto-Faraco, S., and Woldorff, M. G. (2010). The multi-faceted interplay between attention and multisensory integration. *Trends in Cognitive Sciences*, 14(9):400–410.

Tang, X., Wu, J., and Shen, Y. (2016). The interactions of multisensory integration with endogenous and exogenous attention. *Neuroscience & Biobehavioral Reviews*, 61:208–224.

ten Oever, S., Romei, V., van Atteveldt, N., Soto-Faraco, S., Murray, M. M., and Matusz, P. J. (2016). The cogs (context, object, and goals) in multisensory processing. *Experimental Brain Research*, 234(5):1307–1323.

van Atteveldt, N., Murray, M. M., Thut, G., and Schroeder, C. E. (2014). Multisensory integration: flexible use of general operations. *Neuron*, 81(6):1240–1253.

Van der Burg, E., Olivers, C. N. L., Bronkhorst, A. W., Koelewijn, T., and Theeuwes, J. (2007). The absence of an auditory–visual attentional blink is not due to echoic memory. *Perception & Psychophysics*, 69:1230–1241.

Wahn, B., Ferris, D. P., Hairston, W. D., and König, P. (2016a). Pupil sizes scale with attentional load and task experience in a multiple object tracking task. *PLoS ONE*, 11(12):e0168087.

Wahn, B. and König, P. (2015a). Audition and vision share spatial attentional resources, yet attentional load does not disrupt audiovisual integration. *Frontiers in Psychology*, 6.

Wahn, B. and König, P. (2015b). Vision and haptics share spatial attentional resources and visuotactile integration is not affected by high attentional load. *Multisensory Research*, 28(3-4):371–392.

Wahn, B. and König, P. (2016). Attentional resource allocation in visuotactile processing depends on the task, but optimal visuotactile integration does not depend on attentional resources. *Frontiers in Integrative Neuroscience*, 10.

Wahn, B., Schmitz, L., König, P., and Knoblich, G. (2016b). Benefiting from being alike: Interindividual skill differences predict collective benefit in joint object control. In *Proceedings of the 38th Annual Conference of the Cognitive Science Society*, pages 2747–2752. Austin, TX: Cognitive Science Society.

Wahn, B., Schwandt, J., Krüger, M., Crafa, D., Nunnendorf, V., and König, P. (2015). Multisensory teamwork: Using a tactile or an auditory display to exchange gaze information improves performance in joint visual search. *Ergonomics*, 59(6):781–795.

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

Wierda, S. M., van Rijn, H., Taatgen, N. A., and Martens, S. (2012). Pupil dilation deconvolution reveals the dynamics of attention at high temporal resolution. *Proceedings of the National Academy of Sciences*, 109(22):8456–8460.

Yantis, S. (1992). Multielement visual tracking: Attention and perceptual organization. *Cognitive Psychology*, 24(3):295–340.