Perceptual organization and visual attention

Inattention, expectation, and Gestalt integration in the visual system

Alexandre de Pontes Nobre

Doctoral thesis presented to obtain
the double degree of Doctor of Psychology
within the framework of a joint doctorate
Supervisors:
Gustavo Gauer
Johan Wagemans

Porto Alegre/2020

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ACKNOWLEDGEMENTS

I am grateful to many people who participated in the process of producing this PhD thesis. At the Federal University of Rio Grande do Sul, I had the opportunity to meet researchers who produce outstanding science (sometimes under less than optimal conditions): Jerusa Salles, Silvia Koller, and Lisiane Bizarro. In particular, I thank Gustavo Gauer and William Gomes for the discussions and the many suggestions of texts to further my curiosity. Thank you also to the teachers I had at UFRGS since 2011.

At the KU Leuven, I had the privilege of working with people who contributed immensely to my research training and to this thesis. I am grateful to Johan, for receiving me in his lab, where I learned a lot about the neuroscience of perception. Thank you also for the encouragement and supervision, and for the contributions for the thesis. I also express my gratitude to Andrey for teaching me much about EEG, working with me during many EEG recording sessions, and a lot of work during data analysis and writing. Thank you also to Cees for the productive discussions since 2016.

I am grateful to both Johan and Cees for funding me during part of my time in Leuven. I also thank the Coordination of Superior Level Staff Improvement (CAPES) for funding my PhD.

During the PhD years, I learned a lot from many colleagues. I am especially grateful to Jaqueline Rodrigues and Gabriela Melo for working with me on our papers and book chapters. I am also thankful to my colleagues at Biosig and LaFEC: Tuíla Maciel, Roberto Nonohay, Gerson Siegmund, Guilherme Lannig, Ana Clara de Paula, Rebeca Veras, and Marcelle Matiazzo, for many moments of working together. At the KU Leuven, Marcello, Kevin, Carlos, Hannah, Pen, Thiago, Sander, and the folks in the PDL and Gestalt ReVision group. Thank you to Rudy and Christophe for all the help in IT matters.

I also had much personal support during the PhD years. I am grateful to Rodrigo Meleu, for supporting me during tough moments, believing in me, and encouraging me. Thank you for being with me in this journey. Natália Becker, my housemate for two years after returning from Leuven. Diego França, for all the support in the last years of the PhD. My dear G9 friends André Moreno, Marcos Janzen, Murilo Zibetti, Letícia Scheidt, Diogo Sousa, Luciana Cassarino, Augusto Pires, and Jonatas Passos, who were always there to share grad students’ experiences.

Finally, I am grateful to my family, especially my mother, who has always been a source of encouragement for me.

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ABSTRACT

Despite decades of investigation, the relationship between attention and perceptual organization is still unclear. It is largely acknowledged that attention is guided by perceptual organization processes; however, the influence of attention on perceptual organization is much less explored. This thesis aimed to investigate how attention influences perceptual organization. Four studies constitute the thesis. In Study 1, we reviewed how Gestalt psychology and the main theories of attention in cognitive psychology and neuroscience relate attention to perceptual organization. This review showed that, although most current theories predict an influence of attention on perceptual organization, there is a gap between theories that explore the heterogeneity in perceptual organization and theories that explore the variety of attentional phenomena. In Study 2, we conducted a meta-analysis of studies investigating implicit processing of unexpected stimuli during inattentional blindness. This review shows considerable evidence for implicit processing of unnoticed stimuli. In Study 3, we attempted to replicate a previous event-related potential (ERP) experiment on implicit texture segregation during inattentional blindness. The results only partially replicate the original study. We discuss possible reasons for these results and relate to the literature on implicit processing during inattentional blindness. In Study 4, we investigate how temporal expectations influence ERPs evoked by stimuli grouped by common-fate. We show that expectation influences common-fate grouping in more than one point in the time course of perception, and that this influence is stronger for more ambiguous stimuli. In the general discussion, the results from the four studies are discussed in relation to the literature on visual attention and perceptual organization.

Keywords: Visual attention; Perceptual organization; Gestalt; EEG; Expectation.

SAMENVATTING

Ondanks tientallen jaren van onderzoek is de relatie tussen aandacht en perceptuele organisatie nog steeds onduidelijk. Algemeen wordt erkend dat aandacht wordt gestuurd door perceptuele organisatieprocessen; de invloed van aandacht op perceptuele organisatie wordt echter veel minder onderzocht. Dit proefschrift was bedoeld om te onderzoeken hoe aandacht de perceptuele organisatie beïnvloedt. Vier studies vormen het proefschrift. In studie 1 hebben we bekeken hoe Gestaltpsychologie en de belangrijkste aandachtstheorieën in de cognitieve psychologie en neurowetenschappen aandacht relateren aan perceptuele organisatie. Dit toont aan dat, hoewel de meeste theorieën nu een invloed van aandacht op perceptuele organisatie voorspellen, er een kloof bestaat tussen theorieën die de heterogeniteit in perceptuele organisatie onderzoeken en theorieën die de verscheidenheid aan aandacht onderzoeken. In studie 2 hebben we een meta-analyse uitgevoerd van studies naar de impliciete verwerking van onverwachte stimuli tijdens *inattentional blindness*. Deze beoordeling toont aanzienlijk bewijs voor impliciete verwerking van onopgemerkte stimuli. In studie 3 hebben we geprobeerd een eerder *event-related potential* (ERP) -experiment te repliceren over impliciete textuursegregatie tijdens *inattentional blindness*. De resultaten repliceren slechts gedeeltelijk de oorspronkelijke studie. We bespreken mogelijke redenen voor deze resultaten en hebben betrekking op de literatuur over impliciete verwerking tijdens *inattentional blindness*. In studie 4 onderzoeken we hoe temporele verwachtingen invloed hebben op ERP's die worden opgewekt door stimuli gegroepeerd op basis van gemeenschappelijke bestemming. We laten zien dat verwachting de groepering van gemeenschappelijke bestemming op meer dan één punt in de tijd van perceptie beïnvloedt, en dat deze invloed sterker is voor meer dubbelzinnige stimuli. In de algemene discussie worden de resultaten van die studies besproken in relatie tot de literatuur over visuele aandacht en perceptuele organisatie.

Trefwoorden: Visuele aandacht; Perceptuele organisatie; Gestalt; EEG; Verwachting.

CHAPTER 1. GENERAL INTRODUCTION

This thesis investigates the relationship between visual attention and perceptual organization, focusing on perceptual grouping. Specifically, we are interested in the influence of attention on perceptual organization. Gillebert and Humphreys (2015), in a chapter in The Oxford Handbook of Perceptual Organization, listed three questions regarding the relationship between perceptual grouping and attention: how perceptual grouping constrains visual attention; whether perceptual grouping can occur in the absence of focused attention; and whether attention modulates perceptual grouping. This thesis aims to contribute to the exploration of the second and the third of those questions.

Modern discussions on attention frequently refer to the following statement by William James (1918), in his Principles of Psychology: “Everyone knows what attention is. It is the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thoughts” (p. 261). Often, however, this quote is cited in the context of a criticism of the concept of attention. This criticism is motivated by a particular difficulty in defining attention objectively (Rensink, 2015). For example, Anderson (2011) refers to a much less cited quote by James to argue that attention has actually been reified and that “there is no such thing as attention” (Anderson, 2011).

The conceptual problem present in the study of attention has been observed for a long time (Johnston & Dark, 1986; Spearman, 1937), with several authors asserting that attention has multiple meanings, perhaps due to its origin as an ordinary-language term. Allport (2011) illustrates this conceptual problem by listing four possible meanings for the term “attention”: as a relationship between an object and an observer; as a system limitation, such as capacity limits; as control processes or a control system; and as a variety of mechanisms implementing selective control. This multiplicity of meanings remains in the contemporary study of attention: Nobre and Kastner (2014), for instance, in the closing chapter to the Oxford Handbook of Attention, list multiple definitions of attention provided by several prominent authors who contributed to the handbook, demonstrating the lack of consensus in the definition of attention in the literature.

Even if a definition of attention is agreed upon in terms of, for instance, selection, there is reasonable agreement that attention may be guided by multiple factors (Di Lollo, 2018;

Nobre & Kastner, 2014; Scholl, 2001). For example, attention can be directed to features (feature-based attention), objects (object-based attention), and regions in space (spatial attention). Those different types of attention which may or may not be implemented by distinct mechanisms (Allport, 2011; Carrasco, 2011). Neurophysiologically, various mechanisms have also been suggested, ranging from an increase in the tonic firing rate of neurons to higher synchronization across areas (Carrasco, 2014; Nobre, 2012). Some frameworks of attention do address this multiplicity, proposing that attention be conceived as the coordinated operation of a set of processes, instead of a single process, each of those with a particular function and underlying mechanism (Rensink, 2015).

The multiplicity of meanings and mechanisms suggested to fall under the label of attention has been invoked as an argument to dispose of the concept of attention (Anderson, 2011; Di Lollo, 2018; Hommel et al., 2019). It has been suggested that employing the concept of attention does not contribute to the understanding of the phenomena typically meant to be explained by this concept (Hommel et al., 2019). That critique points out that, as a term derived from natural language, attention does not necessarily map onto processes that perform functions usually attributed to attention, such as selectivity.

Indeed, history shows that the empirical study of attention has been guided largely by metaphors (Fernandez-Duque & Johnson, 2002; Watzl, 2017), instead of explicit definitions. Such metaphors are computationally vague and conceptually circular (Di Lollo, 2018). For this reason, some authors have proposed to replace the concept of attention with more biologically plausible constructs (Hommel et al., 2019), like iterative reentry (Di Lollo, 2018). While this is closer to a mechanistic account than the admittedly imprecise term "attention", it remains to be seen too which extent such proposals might account for the multiplicity of phenomena commonly referred to as attentional. Similar attempts to replace attention with other concepts have not received widespread acceptance.

Contrastingly, philosophers of cognitive science have argued against eliminativism – the idea that the concept of attention should be abandoned – and against disunity – the view that there is no *single* thing referred to as attention (Watzl, 2017). Some contemporary work has proposed that attention is a single phenomenon, despite including multiple distinct subpersonal processes (Mole, 2011; Watzl, 2017). The type of phenomenon that attention is, is a subject-level phenomenon (Jennings, 2015): one that refers to an individual subject as a whole, for whom there is something it is like to be experiencing that phenomenon (Watzl, 2017, p. 34). These authors also highlight that conceptual work on attention must focus on the role of attention in organizing phenomenal experience (James, 1918; Mole, 2011; Watzl, 2017).

Selective and Organizational Aspects of Attention

Debates about the functional role of attention date back to at least the 19th century. It has been questioned, for example, whether attention has any specific function at all (Bradley, 1886). William James, in his Principles of Psychology, claimed that it has, and included both selection and organization among its functions (James, 1918). Each of those aspects has received more or less emphasis in psychological theories since then. In cognitive psychology, the selective aspect appears in several conceptualizations of attention that frame the problem from the point of view of an architectural issue or a system limitation (Allport, 1989, 1993). This has been referred to as the “information-pruning” (Watzl, 2017) or “processing optimization” (Huang & Pashler, 2007) function of attention. The selective function of attention is proposed to prevent information overflow in the cognitive system (Carrasco, 2011; Fiebelkorn & Kastner, 2020; Wolfe, 2014).

Other functions, or aspects, of attention have also been examined. Kahneman (1973), for example, distinguished between the more frequently highlighted selective aspect of attention and an intensive aspect, which has to do with arousal and effort. Recently, a theory of attention (Huang, 2010; Huang & Pashler, 2007) distinguished between selection of features from the environment and (conscious) access of such features and their conjunctions. Further taxonomies of attention include a distinction between a selective function and an organizational function that determines how visual experience appears to an observer (Rensink, 2015; Tsotsos, 2013).

Structural approaches to attention view the structure of phenomenal experience as organized by attention in order to allow for flexible action (e.g., Watzl, 2017; Wu, 2017). This organizational aspect of attention strongly relates to the field of perceptual organization, which is particularly associated with Gestalt psychology (Palmer, 2003). This tradition of Psychology influenced cognitive psychology in attributing a role for perceptual organization is the structuring of the visual field in “proto-objects” that are then selected for mental processes such as memory (Kahneman & Henik, 1981; Mack & Rock, 2000; Scholl, 2001). However, the role of perceptual organization in complex cognitive processing was rather limited in classical theories, with organization being much less emphasized then selection. In this section, we discuss these two aspects of attention.

Attention and Selection

The most widely explored function of attention is to select information from the vast amount of sensory inputs that confront the organism (Carrasco, 2011; Chun et al., 2010; Desimone & Duncan, 1995; Rao & Ballard, 2005). According to this view, the barrage of stimulation that impinges on the senses overloads the information processing capacity of the brain (Niebur & Koch, 1998; Pashler, 1998). Selection may be used to indicate either selection for further processing (Pashler, 1998) or selection for entry into consciousness (Srinivasan, 2008). This last aspect has figured in much of the current literature discussing the relationship between attention and consciousness, which are widely viewed as closely related, in spite of being usually considered to be distinct constructs (Dehaene et al., 2014; Koch & Tsuchiya, 2007; Lamme, 2003). Indeed, the same properties of selectivity and organization have been attributed to consciousness by Hochberg (1970), an author rooted in Gestalt Psychology.

In the first decades of cognitive psychology, most classical cognitive studies on attention focused mostly on attention as a filtering mechanism (Mole, 2011). Early cognitive studies inherited the framework put forward by Broadbent (1958), who conceived attention as selection due to a limitation in capacity for information processing (Eimer, 2014; Mole, 2011; Serences & Kastner, 2014). In Broadbent's (1958) model, attention served as a filter or gatekeeper that marked the transition from a parallel processing stage to a serial processing stage. Theories influenced by that framework postulated some kind of filter that interrupted processing at the point in which serial processing could not handle all the information received (Theeuwes, 2010). Those theories were generally divided into two classes of theories, according to the point during cognitive processing in which filtering occurred: early selection theories and late selection theories (Eimer, 2014). Early selection theories argued that stimulus selection occurred at the perceptual level, either on the basis of low-level physical features of the stimulus (Broadbent, 1958) or perceptual ones, and that such selection might be located at sensory areas of the cortex (for example, V1 in the visual modality; Serences & Kastner, 2014). On the other hand, late selection theories proposed that selection occurred following semantic analysis (Treisman, 1964), which occurred later in stimulus processing, either after contact with long-term memory storage or at the response level (Deutsch & Deutsch, 1963). Although the early vs. late dispute guided a large number of studies, the evidence gathered across decades of experiments was unable to settle the issue. This was partly because evidence, both behavioral and neural, was found in favor of both early and late selection (see, for example, Eimer, 2014; Luck & Kappenman, 2012; Serences & Kastner, 2014, for reviews).

Another aspect of attention was discussed in the context of early filter theories, which was related to the selective function of attention: the conception of attention as processing resources (Kahneman, 1973; Navon & Gopher, 1979; Norman & Bobrow, 1975). According to this quantitative view, attention is a type of processing resource that can be invested in a task (Navon & Gopher, 1979), although the exact nature of that resource is unclear (Nobre & Kastner, 2014). In this perspective, some cognitive processes require attentional resources, and are considered “controlled”; whereas others do not require such resources, and are considered “automatic” (Allport, 1993, 2011). This conception of attention is related to the idea of selectivity, in the sense that selection is often considered a consequence of capacity limits (Allport, 1989).

This perspective of attention as resources was adopted by a theory that attempted to settle the dispute between early- and late-selection theories, called Perceptual Load Theory (Cartwright-Finch & Lavie, 2007; Lavie et al., 2014). In Perceptual Load Theory, effects attributable to early and late filters are explained by resource capacity and allocation (Lavie et al., 2004; Lavie & Dalton, 2014). When a subject engages in task with high perceptual load, focusing attention on this task consumes all available capacity. When the task places low demands on the perceptual system, the remaining available attention is allocated to irrelevant stimuli. Thus, according to the perceptual load theory, both early selection and late selection may occur depending on the circumstances in which the stimuli are presented. This theory has successfully explained some seemingly contradictory results from studies employing change blindness and inattentional blindness paradigms (Cartwright-Finch & Lavie, 2007; Lavie et al., 2014). Moreover, in addition to explaining the conditions in which unattended stimuli enter awareness, the theory provides predictions concerning the degree to which unattended stimuli are processed when attention is not available. Specifically, perceptual load theory predicts that when a subject attends to a task and irrelevant stimuli are presented, activity evoked by unattended visual stimuli should decrease with the difficulty of the attended task (Beck & Kastner, 2014), as less capacity would remain under higher load conditions.

A distinct and influential view of attention was proposed to explain the selective aspect of attention, while suggesting neural mechanisms for attentional selection, called the "biased competition hypothesis" (Desimone, 1998; Desimone & Duncan, 1995; Duncan, Humphreys, & Ward, 1997). According to this hypothesis, attention consists in an emergent property of mechanisms of competition for cognitive and behavior control of resources (Desimone & Duncan, 1995). In this theory, when two stimuli are presented within the same receptive field, the neuron's responses compete in a mutually suppressive manner (Spratling, 2008). When attention is directed to a stimulus, however, the response is similar to that observed when the stimulus is presented in isolation (Luck et al., 1997). Such effects have been demonstrated for both single cells and cell populations (Beck & Kastner, 2014). In that theory, attention has both capacity limits and selective aspects: Desimone and Duncan (1995) stated that the two basic phenomena that define visual attention are selectivity and limited capacity.

It is important to stress, however, that despite selectivity and limited capacity being often linked both empirically and theoretically in the literature on attention, the idea of attention as a processing resource or a capacity limit is logically separable from attention as selectivity (Pashler, 1998). For instance, Kahneman (1973) distinguished quite clearly between those functions, in a book (*Attention and Effort*) that influenced much of the literature on capacity limits. Indeed, the view of limited capacity or resources as a whole has been criticized (Navon, 1984), without this implying in a criticism of selectivity (Johnston & Dark, 1986).

The idea of attention as selection is also present in consciousness models in which attention serves to amplify stimulus processing or to make such stimulus globally available for processing by various cognitive systems, with such global availability viewed as a condition for consciousness (Baars, 1988; Dehaene et al., 2006; Pitts et al., 2018). Such theories often incorporate a distinction between attentive and preattentive processes. For example, the global neuronal workspace model of consciousness (Dehaene et al., 2014) presupposes the existence of cognitive modules that constitute a preattentive stage of processing, which precedes an attentive stage wherein the products of earlier stages become conscious.

The view of attention as a gatekeeper for further processing or for entry into consciousness motivated the development of a series of experimental paradigms. An iconic example is Inattentional Blindness (Mack & Rock, 2000; Simons & Chabris, 1999). This phenomenon consists in a frequent inability, by individuals who perform an attentionally demanding task, to report unexpected stimuli or unexpected changes in irrelevant stimuli presented concomitantly to that task. Experiments using this paradigm are often cited as evidence that consciousness demands attention, and that unattended stimuli remain unconscious because they have not been selected for entry into consciousness (Cohen et al., 2012). Related paradigms include change blindness (Simons & Levin, 1997) and the attentional blink (Raymond et al., 1992; Shapiro & Raymond, 2012). Those paradigms, along with inattentional blindness, have been cited to argue that our perception is highly limited, and that only a small part of the visual information presented to an observer is selected for further processing, and, ultimately, for entry into consciousness. That selection is performed by attention (Dehaene et al., 2006).

In sum, the selective aspect of attention, as framed in the classical cognitive literature, is closely related to a hierarchy of processing stages, starting with early sensory analysis, and ending with conscious awareness. Attention is the gatekeeper that bars information from proceeding along those stages, the position of which varies across theories.

Attention and Organization

The selective aspect of attention was emphasized in earlier studies of attention (Pashler, 1998) and still receives much attention (Fernandez-Duque & Johnson, 2002; Jennings, 2012), due to the well-acknowledged fact that the environment presents observers with too much information to process (Carrasco, 2011; Wolfe, 2014). Organization, although mentioned in those theories, is viewed as a consequence of limited processing capacity. Nevertheless, exclusive focus on information selection aspects, which has been referred to as a deflationary view of attention, has been criticized for its inability to explain differences in phenomenal experience due to attention (Watzl, 2017, p. 157).

In recent decades, several studies have established that attention influences not only performance, but also the actual appearance of visual stimuli in perceptual tasks (Carrasco, 2011; Carrasco et al., 2004; Carrasco & Barbot, 2019). Effects of attention on the appearance of stimuli have been observed on a variety of parameters of visual stimuli, such as spatial resolution (Yeshurun & Carrasco, 1998), brightness (Tse, 2005), contrast sensitivity (Carrasco, 2006), perceived color saturation (Fuller & Carrasco, 2006), and perceived spatial frequency (Abrams et al., 2010). Those effects have been observed in behavioral studies

(Beck & Kastner, 2014; Carrasco, 2014), reinforced by neuroimaging data showing increased activation in areas of the visual cortex corresponding to the attended region in the visual field (Beck & Kastner, 2014). Overall, then, it is well-established that attention not only selects information for further processing stages, but also influences the phenomenal appearances of stimuli.

The specific contribution of attention to how individuals perceive the world, according to some proposals (Allport, 2011; Arvidson, 1996; Gurwitsch, 2010b; Jennings, 2015; Watzl, 2014, 2017; Wu, 2017), is that attention organizes the structure of phenomenal experience (Watzl, 2017). This structure brings along a distinct phenomenology to attention. In line with the idea the attention is a subject-level phenomenon, Jennings (2012, 2015) argues that the type of organization brought about by top-down attention is a form of "subject-based organization". This type of organization is not exhausted by organization in terms of features, objects, space or what Jennings (2015) calls "field-based organization" (mutual organization among parts of the perceptual field). Instead, subject-based organization structures conscious experience according to the subject's interests and goals.

Recent philosophical work has developed the idea of phenomenal structure in more detail (Watzl, 2017). Watzl claims that conscious experience has an organizational structure similar to that proposed by James (1918), for whom consciousness had a center-fringe structure, which was brought about by attention. In the phenomenal structure, some parts are more central than others (centrality relations), according to the subject's perspective. The system composed by those parts, called centrality systems, is characterized by the fact that they are experienced together, i.e., consciousness is always integrated. The phenomenal character of such systems depends on the entanglement of all those parts: It includes all the phenomenal parts and their centrality relations. The experience of parts of a system depends on all other parts, and this is constitutive to what attention is. This interrelation of distinct parts of the visual field is a proposition that is also found in Gestalt psychology, but was not present in early cognitive psychology or vision science.

In recent cognitive psychology and cognitive neuroscience, some concrete proposals have been put forward relating attention to organizational principles (Driver et al., 2001; Rensink, 2015; Scholl, 2001). In particular, this discussion has received contributions from Gestalt psychology, arguably the psychological theory that attributed the most importance to organization, particularly in perception (but also in other areas, such as memory; Köhler, 1941). van Leeuwen and colleagues (2011), for example, propose that in Gestalt psychology the concept of attention might be replaced by the concept of figure-ground organization. It is widely acknowledged that attention influences which region of the visual field becomes figure or ground (Wagemans et al., 2012). However, it has been pointed out (Palmer, 1999, p. 283) that the relationship between attention and figure-ground is not so straightforward, since, for example, attention may well be directed to the ground instead of the figure. Moreover, in some cases, attending to a region makes it appear as background instead of figure (Huang & Pashler, 2009). Therefore, there are issues with conflating attention and figure-ground segmentation.

Gestalt Aspects of Visual Experience

Instead of replacing attention with another concept such as figure-ground, investigating the role of attention in the perceptual organization processes described by Gestalt psychologists may be a more promising alternative. Earlier authors have proposed a relationship between attention and Gestalt principles. Aron Gurwitsch (2010a) linked Gestalt psychology to phenomenology in an attempt to describe the structure of conscious experience. He argued that conscious perception of an object necessarily implies organization and formal structure. The structure of conscious experience includes three elements: theme, thematic field, and margin. The theme corresponds to the focus of attention (Gurwitsch, 2010b; Yoshimi & Vinson, 2015), and has a Gestalt nature (or "Gestalt-contexture"), understood as an interdependence between the parts like what was described by Gestalt psychologists. Specifically, parts within a Gestalt-contexture bear a relationship of Gestalt coherence, defined as "the determining and conditioning of the constituents upon each other. In thoroughgoing reciprocity, the constituents assign to, and derive from, one another the functional significance which gives to each one its qualification in a concrete case" (Gurwitsch, 2010b, p. 131). The theme is then "a unitary whole of varying degrees of richness of detail, which, by virtue of its intrinsic articulation and structure, possesses coherence and consolidation and, thus, detaches itself as an organized and closed unit from the surrounding field" (Gurwitsch, 2010b, p. 112).

The theme is surrounded by the an inner surrounding, thematic field; and an outer surrounding, the margin. The thematic field comprises parts of the visual field which are both co-present with and relevant to the theme, while the contents of the margin are merely co-present with the field, but are not relevant to it (Gurwitsch, 2010b). Watzl (2017) examines the idea of relevance that defines the thematic field in Gurwitsch’s view, arguing that two properties characterize this relevance relation: a “coloring periphery” relation, according to which the thematic field alters the appearance properties of the theme; and a “sustaining periphery” relation, according to which the theme is the phenomenal center of experience because of the thematic field. The thematic field, thus, comprises elements in the field of consciousness that color and sustain the theme. The thematic field and the margin are both distinguished from the theme in that they do not have Gestalt-coherence, even though they are also aspects of conscious experience. Thus, for Gurwitsch, the focus of attention has an essential feature in that its contents are organized as a whole according to Gestalt principles.

Gurwitsch’s work has been criticized both regarding the role of the concept of “relevance” in this theory and the Gestalt nature of the theme. Yoshimi and Vinson (2015) argue that the focus of attention is not always organized according to Gestalt principles. Watzl (2017), on the other hand, opposes the idea that all conscious experiences have a thematic field. Nevertheless, features that bear a relevance relationship to the theme, as those that comprise the thematic field, are present in much of our experience, and the idea that objects within the focus of attention have a specific mode of organization offers distinct interpretations of findings from experimental psychology.

The views above claim that organization is an essential feature of attention, understood as a subject-level phenomenon: the organization of the focus of attention depends on the whole field of experience and on the subject’s perspective to what is experienced. Even though these are rather phenomenological accounts and not strictly scientific theories, they may illuminate the study of how attention influences perception, particularly considering how unclear the concept of attention is. One such case is found in the area of perception under conditions of inattention. Classical views treat stimuli outside participants’ focus as unattended, and therefore not accessible to conscious perception. For example, in several inattentional blindness studies, stimuli outside the focus of the participant who performs the task are treated as unattended. Such stimuli are viewed as being rejected for further processing at some stage and are thus excluded from awareness.

Alternatively, objects outside the focus of attention may be distinctly organized. Objects outside the focus of attention have been shown to differ in organization from fully attended objects in many ways: they may appear closer to the subject, have a smaller tendency to become figure, or a smaller tendency to group together (Mack & Rock, 2000).

They may also not be processed to the degree that allows them to be recognized, which led some authors to suggest that inattentional blindness may actually be “inattentional agnosia” (Mole, 2008; Simons, 2000). Inattention studies also suggest that even though perceptual organization does not occur consciously for stimuli outside the focus of attention, conscious perception of those stimuli is not entirely absent (Rensink, 2015). In such situations, perception is often incomplete or lacks detail, being therefore more sparse (Ward et al., 2016). It has been proposed that, when attention is directed elsewhere, perceptual gist or ensemble statistics of stimuli (Alvarez & Oliva, 2009; Chong & Treisman, 2003; Ward et al., 2016) might still be perceived. Rensink (2015) speaks of “fragmentary experience,” a sort of experience which includes features with little intrinsic structure, like non-local structure and shapes. In contrast, perception at the focus of attention is integrated to a greater degree, and may be characterized by more detail or by the presence of relationships absent in stimuli outside the focus of attention.

Thus, investigating the relationship between attention and perceptual organization is relevant for the explanation of how attention influences perception in general, and conscious perception in particular. Given the extensive work in Gestalt psychology to the understanding of perceptual organization, Gestalt principles are an important guide for this study. Therefore, to contribute for this discussion, we propose to investigate the relationship between attention and perceptual organization according to Gestalt principles.

The Present Thesis

In this thesis, we investigate the relationship between attention and perceptual organization in vision. Specifically, we will investigate the influence of visual attention on the perceptual grouping of moving visual stimuli. We initially review the main theories of attention to explore how perceptual organization is framed in those theories. Next, following the questions listed by Gillebert and Humphreys (2015), we report three studies exploring this relationship. Two studies address question 2: can perceptual grouping occur in the (near) absence of attention? The last study addresses question 3: does attention modulate perceptual grouping? In total, the thesis comprises four studies.

Study 1 reviews the main theories pertinent to the study of attention and perceptual organization and examines how they relate those two constructs and their proposals for the current issues in the field of perceptual organization.

Study 2 describes a systematic review of the literature on inattentional blindness and implicit processing of unexpected stimuli, discussing the implications of the methods currently used to the relationship between attention and consciousness.

Study 3 attempts to replicate one of the studies reviewed in Study 2 using EEG to study whether texture segregation of unexpected stimuli occurs during inattentional blindness.

Finally, in Study 4 we manipulate temporal allocation of attention by expectation to analyze how attentional allocation by temporal expectation influences common-fate grouping, as measured by event-related potentials.

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CHAPTER 2. THEORIES OF ATTENTION AND PERCEPTUAL ORGANIZATION

Nobre, A. P. (in preparation). Attention and perceptual organization from Gestalt psychology to cognitive neuroscience.

Abstract

Proposals about the relationship between attention and perceptual organization vary across psychological theories. Historically, theories that attribute a privileged role to attention tended to neglect the importance of perceptual organization processes and vice-versa. However, in the last decades, this divide has narrowed, with attention and perceptual organization being increasingly viewed as related. In this article, we revisit the position of Gestalt psychology on the role of attention on perceptual organization. Then, we review the main theories in cognitive psychology and cognitive neuroscience that propose relations between both processes. We find that, in the last few decades, the relationship between attention and perceptual organization has come to be regarded as bidirectional. However, the increasingly acknowledged heterogeneity of perceptual organization makes this relationship complex and challenges current theories. We conclude by pointing some issues for current theories that connect attention and perceptual organization.

Keywords: perceptual organization; attention; Gestalt; cognitive psychology; cognitive neuroscience

In the visual realm, perceptual organization may be defined as the processes that structure separate visual information into larger coherent units, which are eventually experienced as objects in the environment (Kimchi et al., 2016). Among the psychological traditions of the last century that addressed the problem of organization, perhaps the one that did it most characteristically was Gestalt psychology. Gestalt psychologists postulated that the organization of visual experience occurs according to principles which are not simply the result of association principles (Koffka, 1935; Köhler, 1970), but emerge due to specific organizational processes imposed on experience by the brain (van Leeuwen et al., 2011).

In recent decades, the mainstream view of visual perception has held that perception is hierarchical (Lamme & Roelfsema, 2000; Murray & Herrmann, 2013). In this view, visual processing is divided into stages, from low-level processes, such as light adaptation, to higher level ones, the latter including incorporation of knowledge about objects (McDermott et al., 2001) and conscious aspects of experience (Poljac et al., 2012). Between those levels is mid-level visual processing, including Gestalt phenomena such as perceptual grouping, surface completion, and other perceptual organization processes (Kubilius et al., 2014). An issue to be investigated in this view is the dynamics of visual perceptual organization, especially concerning the question of whether perceptual organization is processed in a bottom-up or top-down manner (Kubilius et al., 2014; Murray & Herrmann, 2013). A related issue is how attention interacts with perceptual organization. In this chapter, we discuss the main theories in psychology and cognitive neuroscience that relate attention to perceptual organization. Here, unless otherwise specified, the term “attention” is used to denote top-down attention instead of bottom-up attention.

Attention and Organization in Gestalt Theory

Organization has been associated with attention at least since William James (1918), along with selection. For James, organization was bestowed upon experience by the subject, who extracted perceptual units from an unorganized whole and structured them in a center-margin structure. Conversely, Gestalt psychologists argued that organization is an autochthonous brain process (Gurwitsch, 2010a; Koffka, 1922). They placed emphasis on factors related to the sensory field (Henle, 2004), as exemplified by the several grouping principles they described (Wagemans, Elder, et al., 2012). The role of forces outside the sensory field, such as factors related to the subject, was generally minimized compared to the role of forces of organization intrinsic in the stimulus (Krechevsky, 1938).

This was the case with attention, which did not have a prominent role in the explanation of experience by Gestalt psychologists (Boring, 1929). Although the term "attention" was used in some of their texts (e.g., Koffka, 1922, 1935), it was frequently either criticized or redefined. Koffka (1922) discussed how the concept of attention was employed as an ad-hoc explanation for problems not accounted for by theories of perception at the time (a criticism that has also been advanced in recent decades, e.g., Anderson, 2011).

This does not mean that, for Gestalt psychologists, the observer had no influence on the organization of experience; they explicitly acknowledged this influence (Henle, 2004). For them, perception of visual stimuli was a function of both "external forces" and "internal forces" (Hamlyn, 1957, p. 58). The former included the physical configuration of stimuli, while the latter included the temporary state of the nervous system (Gurwitsch, 2010b; Koffka, 1938) and the subject's attitude (Koffka, 1938).

The concept of attitude incorporates subject-related factors into organization. Attitude consists in "a readiness to carry out certain structural processes" (Koffka, 1922, p. 547); equivalently, the structure that ensues from the presentation of the stimuli is prepared beforehand by the subject. Experimental tasks in which participants have to compare two stimuli induce a structure, which encompasses the stimuli along with the background and the remainder of the visual field. That structure refers to an undefined whole, the elements of which are characterized by their position in the whole to which they belong (their "member-character"). A structure is primarily determined by the specific organization of the field, consisting of the organization of external stimuli. Nonetheless, it is also determined by the subject's attitude, understood as forces in the dynamic interaction between the behavioral field and the Ego; those forces influence the behavioral field and change its structure. For example, when subjects are confronted with material that lacks intrinsic organization (such as lists of unrelated syllables), they impose their own organization on it (Koffka, 1935; Köhler, 1941). The subject's attitude creates or reduces tension between stimuli, makes one stimulus more likely to appear as figure than ground, and, in general, changes the probability of certain modes of response, which are themselves structures.

In an experimental setting, attitudes could vary due to a multiplicity of factors, such as the design of experiments and the instructions given to participants. Attention is one such factor. For Koffka, attention was an attitude of unspecific directedness to an object which changes the total structure (Koffka, 1922, p. 395). In this view, attention is expected to influence perceptual organization, as it is another element in the field of forces of organization. Some types of attitude appear to bear a connection to experimental tasks currently used to investigate attention, e.g., a search attitude (Koffka, 1935; Köhler, 1941), which resembles the attitude that must be present in visual search tasks (Pashler, 1998). Koffka explicitly linked attention to the figure-ground structure (1922, p. 561), asserting that when an individual attends to a stimulus, they adopt a "figure attitude" toward that stimulus, making it the center of the experience, or giving it a "figure-character". In this way, attention does not merely introduce a stimulus into consciousness, but makes it a figure, with all the phenomenal changes this implies (border-ownership, increased brightness, etc.).

Empirically, this is seen in the famous example of Rubin's ambiguous figure, in which an observer may see either a vase or two faces, and this configuration can be modified by attention. Interestingly, Köhler himself (Köhler & Adams, 1958) investigated the effect of "deflecting attention" on perceptual organization. The participants in this study viewed pictures which they rated in terms of likability, while dot patterns that could group according to grouping principles were presented in the background, varying the distance between the dots. After rating a number of pictures, they were asked to describe the patterns in the background. Next, participants were presented the patterns with no superimposed pictures, and asked to describe them. Köhler and Adams (1958) found that, when participants were attending to another task, dots had to be much closer in order to be perceived as grouped by proximity compared to when they were directly viewed.

That study was criticized due to its experimental design, e.g., differences in occlusion of the dot patterns between the experimental and control conditions (Mack et al., 1992; Mack & Rock, 2000). Those criticisms notwithstanding, the experiment bears a clear resemblance to the design employed by Neisser and Becklen (1975), which was eventually developed into the inattentional blindness paradigm (Mack & Rock, 2000; Rock et al., 1992). This clearly illustrates how Gestalt psychologists considered that attention interacted with external elements of the visual field to organize perception. However, they also stressed that there are limits to the influence of attention on the organization of the field. Öğmen and Herzog (2013) provide examples of configurations in which attention cannot bring forward a part of an object to make it figure, regardless of how it is directed to the object. Thus, although attention could influence organization, its role was theoretically rather limited, and in practice somewhat neglected.

Attention and Organization in Cognitive Psychology

Decades after its initial development, Gestalt psychology eventually declined. Several reasons exist for this decline (Wagemans, Elder, et al., 2012). Progress in other areas of vision science, such as the work by Hubel and Wiesel (1959) on receptive fields using single-cell recording techniques, led to a shift in the field to an atomistic approach (Palmer, 2003), which was incompatible with Gestalt psychology's holistic view. Moreover, the Gestalt psychologists lost influence when most of its proponents moved to the United States (Wagemans, Elder, et al., 2012), where first behaviorism and then cognitive psychology were taking the position of dominant paradigm in experimental psychology.

With cognitive psychology also came a renewed importance to the concept of attention (Kahneman, 1973). In classical cognitive psychology, the standard perspective of the relationship between attention and perceptual organization was largely influenced by Neisser (1967), who proposed that perceptual organization was essentially preattentive. Neisser (1967) explicitly mentioned the Gestalt influence, linking perceptual organization processes ("preliminary operations") to the term "autochthonous forces" used by the Gestalt psychologists. In this early cognitive view, object recognition was achieved by processing stimuli in stages within a hierarchical structure which goes from very simple, local attributes to progressively more complex information as the visual hierarchy is traversed. Attention, in this framework, acts at a later stage, following an early, preattentive stage (Neisser, 1967). Perceptual organization processes such as grouping and figure-ground segregation were considered to occur at the preattentive stage in a bottom-up fashion (Montoro et al., 2014; Palmer et al., 1996). At this early stage, perceptual organization processes structure the world, creating the units to which attention might be directed afterwards (Driver et al., 2001; Moore & Egeth, 1997). One important reason for this was the assumption that, in order for attention to select objects, some perceptual organization must already be present on the visual input, so that the objects can be treated as such by the visual system (Kahneman & Henik, 1981; Mack et al., 1992).

The notion of perceptual organization processes as preattentive was advocated in many traditional cognitive theories of attention (Julesz, 1981; Kahneman & Henik, 1981). That was the case for Feature Integration Theory (Treisman & Gelade, 1980), which did concern itself with the organization of perceptual information. Two stages of processing were assumed, similar to those proposed by Neisser (1967): a preattentive stage and an attentive stage. According to the theory, processing of basic features, such as color or orientation, was preattentive, being executed in parallel by the visual system (Treisman & Gelade, 1980). Each feature is registered independently in a separate feature map (Treisman, 1982), which represents the spatial arrangement each feature. The common spatial representation of those features allows them to be conjoined later, which is achieved by attention. Therefore, processing of conjunctions of features demanded attention, basically as a binding mechanism, and was conducted serially (Treisman, 1998; Treisman & Gelade, 1980). Although such a role of attention in binding implies that attention influences the organization of visual objects, this theory makes a distinction between Gestalt properties such as closure and conjunctions of basic features (Treisman & Paterson, 1984). Gestalt properties such as closure and symmetry were viewed themselves as basic features, and as such, were detected preattentively, so that further perceptual processing and attentional allocation might be carried out on the objects formed on the basis of those properties (Pomerantz & Portillo, 2015; Treisman & Paterson, 1984). Moreover, because basic features are represented along with their locations, when they are grouped together in regions of space, they can be inspected as a group pretattentively (Treisman, 1982). When they are not spatially organized, however, attention is needed to inspect more than one item.

The criteria used to classify features as basic was based on Garner’s (1974) distinction between integral versus separable features. Integral features were conjoined automatically, whereas separable features required attention to be integrated (Treisman & Gelade, 1980). The notion of basic feature was also influenced by early neurophysiological research (Hubel & Wiesel, 1959) in vision that indicated specialized detectors for visual attributes such as orientation and color (Nakayama & Joseph, 1998; Quinlan, 2003). These criteria were operationalized experimentally through pop-out in visual search, immediate texture segregation or grouping, formation of illusory conjunctions, and search asymmetries (Pomerantz & Portillo, 2015; Treisman & Gormican, 1988; Treisman & Paterson, 1984; Wolfe, 2001). In the specific cases of grouping and texture segregation, because these processes were considered to occur preattentively, Feature Integration Theory predicted difficulties in grouping or segregation for conjunctions compared to single features (Treisman & Gelade, 1980; Treisman & Paterson, 1984).

Later theories based on Feature Integration Theory include other concepts such as priority maps or salience maps (such as Guided Visual Search; Wolfe, 2014), which allows top-down influences such as goals and expectations to influence visual information processing (Gillebert & Humphreys, 2015). In general, though, the focus remains on binding of features as viewed by Treisman’s original theory (Treisman & Paterson, 1984), with the search for features themselves being an object of investigation (Wolfe, 2014). This binding process was later developed to occur in multiple stages (Humphreys, 2016), with an initial bottom-up feature integration stage followed by a later attentional stage in which top-down feedback confirmed weaker perceptual hypotheses.

A similar notion of independent and combined features is present in the theory of effortless perception described by Julesz (1981a, 1981b). The term “effortless perception” was operationalized as perception of brief stimuli (i.e., presented for less than 160 ms), being also called “immediate perception”. The term was also likened to Neisser’s concept of preattentive perception by Julesz (1981b). The theory distinguishes between preattentive perception and perception based on an image’s second-order (or higher) statistics, which is a global property. The preattentive system cannot discriminate between images with identical third-order statistics or higher. Whereas images with distinct first-order statistics are detectable preattentively, for second-order statistics, two types of specialized detectors are postulated: class A detectors, which discriminate between scenes which have equal first-order statistics but differ in second-order statistics; and class B detectors, which detect specific topological features for images that have identical second-order statistics. These features – which include colors; elongated blobs with specific orientations, widths, and aspect ratio; and those blobs’ terminators – were called “textons” and were regarded as basic elements of preattentive perception. Combinations of those elements and differences in higher-order statistics could be processed preattentively. Hence, the theory maintains the distinction between attentive and preattentive systems proposed by Neisser (1967), with initial parallel processing being followed by serial processing.

In sum, most early cognitive theories assumed that perceptual organization processes did not demand attention. Organizational processes were viewed as preceding attention in the time course of perceptual processing, although the elements that supported such preattentive vision varied across theories.

Influences of Perceptual Organization on Attention

However, perceptual organization and attention were not completely unrelated in those early theories, because organizational processes were assumed to influence attentional allocation. That had already been proposed by Gestalt psychologists, who stated, for instance, that figures draw attention whereas backgrounds are left relatively unattended (Wagemans, Elder, et al., 2012). This was considered logically necessary by early cognitive psychologists, who claimed that attention operated on perceptual units, or objects (Kahneman & Henik, 1981). Since those perceptual units were created by perceptual organization processes, it followed that perceptual organization had to occur before the operation of attention (Neisser, 1967).

The view that perceptual organization influences attention was also arrived at after much empirical research in the cognitive tradition (e.g., Haimson & Behrmann, 2001; Kimchi et al., 2007; Yeshurun et al., 2009). In partial report tasks, items that group according to Gestalt cues tend to be reported (or missed) jointly, suggesting that attention spreads across members of groups (Kahneman & Henik, 1981). Attention can be directed to spatially dispersed objects that group according to Gestalt principles (Driver & Baylis, 1989). Objects created by Gestalt factors lead to object-based attentional effects that resemble those observed when whole objects are presented (Kramer & Jacobson, 1991). For example, responses to visual targets are faster when those targets are preceded by attention-directing cues presented on the same object compared to when they are presented on other-objects, even when the distance between objects is smaller than the distance between targets presented on the same object (Egly et al., 1994). Gestalt cues also lead to easier judgements about two features when they belong to the same object, compared to when they belong to different objects (e.g., Duncan, 1984). Objects built on the basis of Gestalt factors of collinearity and closure capture attention automatically even when they are task-irrelevant and unrelated to (e.g., are unconnected and unpredictive of) targets of a main task (Kimchi et al., 2016).

Support for the influence of perceptual organization on attention also came from the investigation of competitive interactions of simultaneously presented stimuli (Beck & Kastner, 2014). According to the biased competition model of attention, stimuli elicit smaller competition among themselves when grouped (Desimone & Duncan, 1995). In light of behavioral evidence that grouped objects behave as wholes when competing for representation or control of behavior, it was assumed that visual objects are organized according to grouping rules, after which competitive interactions occur which preserve those groupings (Desimone & Duncan, 1995). Experiments have shown that stimuli that group according to similarity indeed exhibit less competition that ungrouped stimuli (Beck & Kastner, 2007). Likewise, inducers of Kanizsa figures (Kanizsa, 1976) compete less when they are oriented so as to form an illusory figure than when their orientations disrupt the illusion (McMains & Kastner, 2010). Neurophysiological results also showed that figure-ground mechanisms such as border-ownership assignment compete for attention (Qiu et al., 2007).

Overall, the view that perceptual organization influences attention has not been contentious for any of the major frameworks (Gestalt psychology and theories in cognitive psychology) examined here. However, attention a) was considered a relatively late process; and b) influenced following, but not preceding processes, i.e., processes higher up in the visual hierarchy, in the case of vision. Even though, in those theories, attention did influence the organization of visual experience given its proposed role in binding (Treisman & Gelade, 1980; Treisman, 1998), this role was limited to object formation, which is distinct from object formation (Kubovy & Van Valkenburg, 2001).

Attentional Influences on Perceptual Organization

The theoretical and empirical work reviewed here show that attention and perceptual organization were not unrelated. Nonetheless, according to classic views, the relationship between those constructs was mostly one-sided: perceptual organization influenced attention, but it did not depend on attention. The capture or spread of attention according to Gestalt factors was considered automatic (Wannig et al., 2011). Later evidence, however, indicated that perceptual organization did not necessarily take place early. Palmer et al. (1996) showed that grouping occurs under conditions of amodal completion, which was classically considered to occur relatively late in visual processing. Grouping is also influenced by lightness constancy and by the presence of illusory contours (Palmer, 2002; Palmer et al., 2003; Palmer & Nelson, 2000), providing further evidence against grouping as an early visual process.

Further studies also showed that perceptual organization is not purely preattentive or automatic (e.g., Barbot et al., 2018; Freeman et al., 2001, 2003; Liu et al., 2006; Volberg et al., 2013). For example, in one study (Houtkamp et al., 2003) participants had to attend to one of two intersecting curve segments and detect a color change in one of those segments. They observed that participants reported a color change more reliably when it occurred in the attended segment compared to the unattended segment. Because tracing a curve segment that intersects with another requires grouping segments by collinearity and connectedness, the authors concluded that such grouping demands attention. Evidence for the involvement of attention in perceptual organization also came from non-behavioral studies, such as that by Han and colleagues (2005), who used EEG to show that attentional modulations of grouping can be observed as early as 100 ms post-stimulus presentation.

Results such as those prompted the emergence of views proposing that perceptual organization occurred in more than one moment in the time course of perceptual processing. Currently, perceptual organization is thought to occur at multiple stages of perceptual processing, across multiple levels of the visual hierarchy (Wagemans, Feldman, et al., 2012). In such a framework, attention and perceptual organization mutually constrain each other (Kimchi et al., 2016). Within this view, attention may influence perceptual organization in one of several stages, in line with the consensus in attention research that the prioritization of information by attention may occur at multiple stages (Humphreys, 2016; Nobre & Kastner, 2014).

In this contemporary view, there is an effort to find mechanisms that connect attention and perceptual organization. One example is the concept of feature map described in Feature Integration Theory (Quinlan, 2003; Treisman, 1982), which is present in later theories with slightly distinct consequences for perceptual organization. The Boolean map theory of attention (Huang et al., 2007; Huang & Pashler, 2007) proposes that access to visual features occurs through Boolean maps, which consist of representations of features in space, with the constraint that only one feature value per dimension can be present in a single Boolean map, although multiple dimensions may be represented in the same map. This theory makes the particular prediction – concurring with current views that consider multiple types of grouping as heterogeneous – that grouping by similarity, but not by proximity, connectedness or other low-level types of grouping, is mediated by feature selection, which is itself an attentional process. Thus, at least one type of grouping demands attention. Furthermore, in this account, grouping by similarity is achieved by first constructing a Boolean map with a certain feature (e.g., shape or color) and then applying grouping by proximity to the objects that have the selected feature (Huang & Pashler, 2007). This implies that the same grouping process – grouping by proximity – can occur earlier or later in distinct situations. The different moments in which grouping by proximity can occur may even constitute a subject characteristic to which individual differences may apply: different groups of participants rely either on preattentive or attentional mechanisms, as evidenced by distinct grouping sensitivity of event-related potential (ERP) components C1 and P1 (Nikolaev et al., 2008).

The view that grouping may occur in several points along the visual hierarchy was also proposed for grouping by common-fate (Levinthal & Franconeri, 2011), with direction of motion constituting the relevant feature value within the map. Levinthal and Franconeri (2011) tested and corroborated the hypothesis that only one common-fate group may be selected at one time, suggesting that such type of grouping is attentional. Although later studies contested the predictions of Boolean map theory on grouping (Kubovy & van den Berg, 2008), the theory contributes to the debate by proposing mechanisms that approximate feature binding and perceptual grouping, and by explicitly stating how attention influences each of those processes (Huang, 2010; Huang & Pashler, 2007).

Current theories draw on both behavioral and neurophysiological evidence to explain how attention influences perception at both behavioral and neural levels. Neurophysiological studies have employed a variety of measures that allowed experimenters to bypass the limitations of behavioral measures and detect attentional processing in specific brain areas and moments in time. The evidence accumulated from such studies argued against the view that attention does not influence low-level visual processing. For example, single unit recordings showed that attention influenced processing in a variety of areas, such as V4, V2, MT, and LIP (Serences & Kastner, 2014). Neuroimaging studies showed that, under certain circumstances, attention may influence activity even in low-level visual areas, including V1 and the lateral geniculate nucleus and superior colliculus (Cutrone et al., 2014; Martinez et al., 1999). Because perceptual organization is considered to involve (but is not limited to) early visual processes, those results argued against the view that perceptual organization is preattentive.

Early computational models proposed to solve the problem of perceptual organization in the brain employing only feedforward mechanisms, but, given the evidence of top-down effects on perceptual organization, recent models rely increasingly on modulation by top-down mechanisms (Lee, 2003). This change was partly motivated by the amount of recurrent connections in the brain, leading to the proposal that such connections may allow attention to influence early visual processing through feedback from higher- to lower-level areas (Kimchi, 2009). In more recent models of perceptual organization, those connections have been proposed as links between mechanisms of visual attention and perceptual organization. For example, von der Heydt (2015) proposed a model for figure-border ownership assignment in which higher-level neurons, called ‘G-cells”, sum the signals of lower-level border-ownership neurons or ‘B-cells’. These G-cells represent objects and thus provide a circuitry for object-based attention, implemented in the form of feedback loops that enhance the responses of B-cells. Therefore, G-cells are able to enhance the activity of cells connected to the same object when attention is directed to that object.

Studies showing attentional effects in very low-level areas, such as the lateral geniculate nucleus (O’Connor et al., 2002), also suggest that early attentional effects are not only the result of feedback activity from higher areas through reentrant pathways. Evidence from ERPs , which have high temporal resolution, also played a role in this argument (Eimer, 2014) by showing effects of attention on the C1 ERP component. This wave peaks around 70 ms post-stimulus, with an onset as early as 50 ms post-stimulus (Serences & Kastner, 2014), and arises from area V1 (Di Russo et al., 2002). Despite earlier studies having found no modulation of the C1 wave by spatial attention (Luck & Kappenman, 2012), recent evidence suggests that attention does modulate this component under specific circumstances (Kelly et al., 2008; Nikolaev et al., 2008; Slotnick, 2018), although the issue is currently under debate (Ding et al., 2014). These results dovetails with findings from single-unit and neuroimaging studies of attentional modulation of V1 activity (Martinez et al., 1999).

Current theories thus propose that many attentional effects may arise due to local interactions both within and across cortical regions (Buschman & Kastner, 2015; Kanai et al, 2015). Biased competition (Desimone & Duncan, 1995), in particular, has been incorporated into many models that aim to explain attention at a mechanistic level (Lee, 2003; Spratling, 2008b; Vecera & Behrmann, 2001). This theory proposes that competition within a given level of the cortical hierarchy is modulated by feedback, which enhances activity consistent with the top-down representations (Desimone & Duncan, 1995; Spratling, 2008b). This allows not only to implement effects of attention on perceptual organization through the operation of recurrent connections, but also to take into account contextual influences (Lee, 2003; Spratling, 2008b).

Biased competition was incorporated into a theory called “Incremental Grouping Theory” (Roelfsema, 2006; Roelfsema & Houtkamp, 2011), which deals explicitly with the issue of perceptual organization. This theory distinguishes between two types of grouping. The first type is base grouping, which occurs at the level of single neurons in a feedforward sweep. The second type, incremental grouping, refers to excitatory and inhibitory interactions that occur between neurons representing the same object. According to the theory, the pattern of excitation between, for example, collinear contour elements emerges within a local association field, which arises from recurrent processing mediated by feedback from higher visual areas or by horizontal connections in V1. Base grouping occurs preattentively, whereas incremental grouping occurs through enhanced responses via recurrent connections which take time to spread through the network; these responses correspond to the allocation of attention. Thus, the theory incorporates a transition from a preattentive to an attentive stage, and in this aspect it is similar to Feature Integration Theory (van Leeuwen, 2015). According to Roelfsema (2006), the theory makes some similar predictions to Feature Integration Theory. However, whereas in Feature Integration Theory Gestalt grouping occurs preattentively (Treisman & Gelade, 1980; Treisman & Paterson, 1984), in Incremental Grouping Theory this is the case only for some types of grouping.

Another framework that has become popular in the last decades and that attributes an important role to backward connections is predictive coding (Gordon et al., 2019; Rao and Ballard, 1999; Spratling, 2008a). In common with biased competition, predictive coding proposes that visual stimuli compete for activation in the visual cortex, and that attention biases such competition (Spratling, 2008b). In this family of models, perception arises in hierarchical neural networks from the interaction of top-down activity, in the form of predictions about the input to be received by the system, and bottom-up activity consisting of prediction (residual) errors between higher-level predictions and lower-level evidence (“surprise”), which are carried via feedforward connections to higher layers of the network (Rao & Ballard, 1999). Predictions and errors are represented by distinct populations of neurons in each layer (Rao & Ballard, 1999). In predictive coding, Gestalts arise from statistical regularities that are used as predictions by the visual system (Van de Cruys & Wagemans, 2011). Thus, perceptual organization is imposed by the brain on the world by the iterative matching of predictions about organizational patterns to the visual stimulation. Grouping leads to reduced activity in lower areas (Friston, 2010), suggesting that higher-level Gestalt predictions explaining away prediction errors in lower-level areas (Wagemans, 2018).

In predictive coding, attention functions as a mechanism that optimizes precision estimates from ascending mechanisms (Hohwy, 2013). This precision adjustment is implemented by gain control mechanisms of excitability of neuronal populations, phase synchrony within cortical regions, and modulation of alpha oscillations across cortical regions (Kanai et al., 2015). This precision modulation effectively increases the gain of bottom-up signals from neurons that encode precision estimates (Friston, 2009) and are associated with both attention and binding (Kanai et al., 2015). Thus, in predictive coding, attention increases the influence of error signals on the predictions from higher levels, leading to greater integration of bottom-up signals with predictions (Gordon et al., 2019). This results in attention leading the visual system to optimize inference-making about the world. In this framework, attention may contribute to perceptual organization by adjusting hypothesis about configurations (for instance, grouping patterns) to the stimuli.

This account leads to heterogeneous influences of attention on grouping. That is, because attention contributes to reduce uncertainty, its effects are bound to be larger when the uncertainty is greater in the visual stimulus. When grouping cues are weak, the contribution of increased precision of error estimates should be larger than when grouping is strong. This resonates with the assertion by Gestalt psychologists that the organization imposed by the subject on the visual stimulation is increased when such stimulation lacks intrinsic organization (Henle, 2004). This also echoes early studies suggesting that the distance needed for stimuli to group is reduced when those stimuli are attended (Köhler & Adams, 1958). In the modern experimental literature, such a difference has been observed in studies investigating biased competition, in which attention reduces competition to a greater degree for weak groupings than for strong groupings created by Kanizsa inducers (McMains & Kastner, 2011). Additionally, it has been observed that attending to moving dot stimuli that group by common-fate increases the perception of coherence in the motion, i.e., participants perceive a greater percentage of dots moving together when stimuli are attended than when they are unattended (Liu et al., 2006).

In the Bayesian variety of those models, perception is produced by the conjunction of hypothesis about the visual scene, provided by the feedforward input, and the priors provided by feedback from higher areas (Lee, 2003). In each step along the visual hierarchy, information from higher-level areas constrains the information of lower-level areas, either increasing or attenuating the corresponding activity. Feedback from priors provides carries contextual information that contributes to perceptual organization. Attention is one such type of feedback, which may be incorporated as priors arriving from higher regions. For example, feedback from the dorsal pathway may bias pool of neurons processing corresponding to specific regions or space, implementing effects of spatial attention (Lee, 2003). Similar mechanisms implement object-based attention and modulate lower-level activity of neurons to arrive at representations of integral objects and of Gestalts. Due to the reciprocal connections between layers in the hierarchy, attentional modulation may extend to very low levels of visual processing, the same being the case for feedback due to perceptual organization.

Other mechanisms are also proposed to lie in the interface between attention and perceptual organization in recent integrative models of attention, including neuronal oscillations (Fiebelkorn & Kastner, 2019), and normalization (Lee & Maunsell, 2009; Reynolds & Heeger, 2009). However, the extent to which the various mechanisms involved in attentional modulation are related to perceptual organization has been developed only briefly. A recent perspective (Buschman & Kastner, 2015) incorporates such mechanisms, along with biased competition, within a theory of attention as prioritization of object representations there are relevant for action. The theory builds on the assertion that the visual system learns the statistical regularities of the objects, which are represented within a distributed neural network through learning (Simoncelli & Olshausen, 2001). Lateral inhibition implements normalization processes that result in competition between stimuli, which boosts relevant representations and suppresses irrelevant ones. Attentional modulation of inhibitory interneurons is also responsible for generating high-frequency oscillations which are associated with attention (Fiebelkorn & Kastner, 2019) and enabling communication across distinct cortical and sub-cortical regions (Buschman & Kastner, 2015). Due to the statistical regularities present in the neural network, selection of an object by attention leads to a spread of attention that boosts the representations throughout the object. This mechanism is proposed to account for perceptual organization according to Gestalt rules. However, this mechanism is quite general, and its specific role in relation to perceptual organization is not the object of much focus in the theory.

Thus, recent proposals of neural mechanisms to implement attention accommodate the idea that attention influences perceptual organization. Crucially, in contrast to classical theories, they propose that attention can modulate perception not only in later stages of perception, but also in very early stages. Moreover, this modulation does not need to arise from higher cortical regions, but may emerge from interactions within a cortical regions by processes of competition and normalization (Buschman & Kastner, 2015; Spratling, 2008b).

Heterogeneity in Perceptual Organization

One important point made in the current literature in the field of perceptual organization the heterogeneity of this construct, which encompasses different processes occurring at multiple levels (Hochberg, 1981; Kimchi, 2009; Wagemans, 2018). Perceptual organization comprises both grouping and figure-ground segregation (Kimchi et al., 2016; Koffka, 1935). Grouping itself is not a unitary process and is guided by a variety of stimulus factors, such as proximity, similarity (of color, size, and shape, among others), common fate, symmetry, parallelism, continuity, closure, common region, element connectedness, synchrony, and generalized common fate (Kimchi et al., 2016; Wagemans, Elder, et al., 2012). Indeed, the concept of grouping comprises distinct processes of unit clustering and shape formation (Kimchi, 2009). Wagemans (2018) has proposed five distinct grouping operations to refine the general notion of grouping: clustering, segregating, linking, layering, and configuring. Grouping by each factor may consist of distinct interactions among those operations (Kimchi, 2009; Wagemans, 2018) and may occur at different levels of the visual hierarchy (Brooks, 2015). Theoretical explanations of the relationship between attention and perceptual organization processes such as grouping have to consider possible differences in mechanisms across types of grouping.

Empirically, differences in effectiveness and in behavioral patterns for the distinct types of grouping have been obtained for a long time (e.g., Kahneman, 1973). For example, behavioral results have suggested that grouping by proximity occurs earlier than grouping by similarity (Ben-Av et al., 1992; Ben-Av & Sagi, 1995). Additionally, grouping by proximity has observable effects on early ERP components, whereas grouping by similarity shows effects on later potentials (Han et al., 2001, 2002). Likewise, collinearity and similarity also exerts effects on ERPs within different time windows (Casco et al., 2009). Moreover, distinct grouping cues interact, sometimes working together, sometimes competing with each other. Pitting grouping cues agains each other reduces the strength of each grouping factor (Han, 2004; Kubovy & van den Berg, 2008; Quinlan & Wilton, 1998; Rashal et al., 2017; Villalba-García et al., 2018).

The effects of a number of variables, such as stimulus characteristics (e.g., color, orientation, luminance; Kimchi, 2009; Wagemans, Elder, et al., 2012) and top-down factors such as learning (Brooks, 2015), differ across types of grouping. This is also the case for visual attention (Kimchi & Razpurker-Apfeld, 2004; Öğmen & Herzog, 2013): grouping processes differ in their attentional demands, such that grouping by some factors seems to occur in the (near) absence of attention, whereas others do not. Empirical evidence for this comes from studies employing the inattention (or inattentional blindness) paradigm (Kimchi, 2009; Kimchi et al., 2005; Kimchi & Razpurker-Apfeld, 2004; Rashal et al., 2017; Russell & Driver, 2005). For example, grouping by proximity and color similarity has been observed under inattention (Kimchi & Razpurker-Apfeld, 2004; Rashal et al., 2017; Russell & Driver, 2005), in contrast with grouping by shape similarity, which seems to require attention (Kimchi & Razpurker-Apfeld, 2004; Rashal et al., 2017). Furthermore, those studies suggest that those differences may be explained at the level of the subprocesses underlying grouping. Kimchi (2009) argues that attention is needed when both element segregation and shape formation are involved in grouping.

Distinct grouping factors also differ in the temporal dynamics of their modulation by attention. For example, grouping by some factors may be modulated by attention at an early stage of processing, whereas others are modulated later. Han et al. (2005) showed that attentional modulation of grouping by proximity was observed at around 100 ms post-stimulus, whereas in the case of grouping by similarity such modulation was detected later, at 250 ms post-stimulus.

The difference across types of grouping is predicted by some of the theories reviewed above. For example, grouping by similarity does depend on perceptual analysis to a larger degree than grouping by proximity. The Boolean map theory of attention (2007), which incorporates several concepts of Feature Integration Theory, distinguishes between those two types of grouping. Boolean map theory predicts that the attentional demands of grouping by similarity are different from those of grouping by proximity or connectedness (Huang, 2015). Most characteristically, Incremental Grouping Theory (Roelfsema, 2006; Roelfsema & Houtkamp, 2011) explicitly distinguishes between base (preattentive) and incremental (attentional) grouping. Other neurophysiologically inspired theories, however, do not approach this issue (Buschman & Kastner, 2015; Fiebelkorn & Kastner, 2019).

Conclusions

The literature reviewed in this chapter points that attentional influences on perceptual organization are predicted by most current theories of attention, in contrast to the earlier literature. However, an important problem is the nature of the relationship between attention and individual perceptual organization processes. Although recent theories have made progress in the direction of specifying mechanisms of attentional influence on perceptual organization, there is still a gap between theories rooted in attentional phenomena and theories of perception that include the issue of perceptual organization, in that theories of one group tend to be inespecific regarding phenomena from the other group.

The theories that deal with the heterogeneity of perceptual organization are the ones that were proposed to explicitly tackle this issue, such as Incremental Grouping Theory (Roelfsema et al., 2011). However, in many instances attention is discussed in terms of the “spread” of attention, which does not account for the the variety of attentional processes. Theories of predictive coding (which are not restricted to perception, although the bulk of the evidence in favor of those theories comes from studies on perception), for example, may handle well many perceptual organization phenomena, but have been criticized for not accounting for instances of voluntary attention (Ransom et al., 2017). On the other hand, recent theories of attention discuss perceptual organization in little detail. In most theories, a differentiation between grouping processes and their attentional demands is lacking. Buschman and Kastner (2015), for example, only briefly touch the issue of Gestalt organization.

This heterogeneity of perceptual organization processes is observed in the difference in attentional demands and susceptibility to attentional modulation across grouping factors, as shown by the studies on inattention reviewed here. Furthermore, there is also heterogeneity in the processing stage in which the influence of attention on perceptual organization occurs, as revealed by EEG studies such as Han et al. (2005) and Villalba-García et al. (2018). This issue is not addressed in many of the theories reviewed above, although some of them (e.g., Huang & Pashler, 2007) distinguish between grouping by proximity and grouping by similarity in terms of processing stages.

Recent empirical studies (e.g., Rashal et al., 2017) suggest that these differences in attentional demands and in temporal dynamics might be due to distinct subprocesses that constitute perceptual organization, such as element segregation and shape formation. This suggests that, theoretically, an account of the relationship between attention and the distinct types of perceptual organization processes needs to distinguish between the operations that underlie those processes, as suggested by Kimchi (2016) and Wagemans (2018). Empirically, it may not be possible to derive general conclusions about the attentional demands of grouping based on experimental investigation of a single or a few grouping factors (Kimchi, 2009). Instead, the different grouping cues need to be investigated one by one (Rashal et al., 2017).

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CHAPTER 3. IMPLICIT PROCESSING DURING INATTENTIONAL BLINDNESS: A SYSTEMATIC REVIEW AND META-ANALYSIS

Paper under review

Nobre, A. P., Melo, G. M., Gauer, G., & Wagemans, J. (2020). Implicit processing during inattentional blindness: A systematic review and meta-analysis. Manuscript submitted for publication.

Abstract

The occurrence of implicit processing of visual stimuli during inattentional blindness is still a matter of debate. A better understanding of this issue may ultimately offer insights into the relationship between attention and consciousness. To assess the evidence available in this debate, we conducted a systematic review of papers that explored whether unexpected visual stimuli presented in inattentional blindness designs are processed despite not being reported by participants. In a second step, we employed meta-analysis to combine 51 behavioral experiments and investigate the statistical support for such implicit processing across experiments. The results showed that visual stimuli can be processed when unattended and unnoticed. Additionally, we reviewed the tasks used to assess participants’ awareness of the unexpected stimuli and used a meta-analytic model to search for indications of awareness of the unexpected stimuli across experiments. The results showed no evidence that participants were aware of the unexpected stimuli. Furthermore, we observed that a variety of procedures were employed to assess participants’ awareness of the stimuli, adopting different criteria which are not always described in detail. We discuss the implications of these results for the study of implicit processing and the role of attention in visual cognition.

Keywords: implicit processing; inattentional blindness; unconscious processing; systematic review; meta-analysis

The relationship between consciousness and attention has been examined by several empirical studies in the last decades, in addition to a body of theoretical work on this matter (Dehaene et al., 2006; Lamme, 2003; Mole, 2008; Pitts et al., 2018; Van Boxtel et al., 2010). Some authors propose that attention and consciousness are completely dissociable (Van Boxtel et al., 2010), with consciousness depending mainly on stimulus features, such as duration or contrast, rather than on attentional factors. Other views assume that the two processes are closely related, often considering attention as necessary for consciousness (see Lamme, 2003, for a discussion of several possible relationships).

Dehaene et al. (2006) proposed a taxonomy for conscious and unconscious states in which both attention and stimulus strength influence whether a stimulus becomes conscious but exert distinct effects. The authors propose that an attended but weak (e.g., masked) stimulus elicits strong feedforward activity, but no recurrent activity, and can be primed only to superficial levels of processing. In contrast, a strong but unattended stimulus elicits local recurrent activation, and priming at multiple levels, but low fronto-parietal activity. In this framework, unconscious stimuli may lead to different neural and behavioral consequences, depending on the method adopted to render them unconscious.

A common approach to investigate the correspondences between attention and consciousness consists in manipulating participants' level of attention. Experimenters attempt to create situations in which stimuli that are consciously perceived in ordinary circumstances are kept unconscious while being unattended by participants. Several paradigms have been developed following this rationale, such as attentional blink, change blindness, and inattentional blindness.

In the attentional blink, two targets are presented rapidly within streams of visual stimuli, and detection of the second target is hindered by the task of identifying the first target when stimulus onset asynchrony (SOA) between both targets is between 200 and 500ms (Marois et al., 2004). Using this design, Sergent et al. (2005) investigated the stages of processing in which attention might modulate the perception of undetected stimuli utilizing event-related potentials (ERPs). Whereas the early P1 and N1 waves were not influenced by the occurrence of the attentional blink, later components were affected. The observed differences in ERPs suggest that the causes of the attentional blink lie in later stages of processing, such as working memory updating (Luck & Kappenman, 2012).

A recent study (Fahrenfort et al., 2017) contrasted the effects of attention and stimulus strength on visual perception, using multivariate classification analysis of electroencephalogram (EEG) data. The activity evoked by the presentation of Kanisza figures made unconscious by either masking or attentional blink was decoded. They found that EEG could be used to decode both perceptual integration and feature contrast for stimuli during attentional blink; conversely, decoder accuracy for perceptual integration was impaired for masked stimuli, indicating that perceptual integration was disrupted in the latter case (corroborating earlier results, e.g., Fahrenfort et al., 2007). In both studies, the evidence may be interpreted as indicating that perception is largely unaffected by the presence or absence of attention − as operationalized by the attentional blink paradigm.

The phenomenon of change blindness shares some characteristics with the attentional blink, including high stimulus strength with limited and no top-down attention (Rensink, 2000). However, it specifically involves the impaired detection of sudden perceptual changes masked by visual disruptions, such as blank screens, eye blinks, or saccades (Simons & Levin, 1997). An EEG study (Busch et al., 2010) argued that change blindness does not result solely from failures of attention, but also from mechanisms for storing and comparing changes between scenes, which may correspond to working memory.

Finally, the phenomenon of inattentional blindness is characterized by a lack of conscious awareness of an unexpected stimulus (US; also referred to as critical stimulus), which is presented while an observer performs some attentionally demanding task (Mack & Rock, 1998). The US is usually visual (event though there are extensions of inattentional blindness employing stimuli in other modalities, e.g., Raveh & Lavie, 2015), and can be either a simple stimulus, like a grating, or a change in stimulus configuration, like Gestalt grouping by similarity (e.g., Moore & Egeth, 1997). In the original version of the inattentional blindness paradigm (Mack & Rock, 1992), participants were explicitly asked if they had noticed the occurrence of the US. When participants could not report its presence correctly, processing of the US was assumed not to have occurred (Mack & Rock, 1992).

A typical inattentional blindness experiment is divided in three phases (Mack & Rock, 1998). The first phase is called inattention phase, since at this point participants have not been informed about the presence of the US. After some trials, participants are alerted about the US, e.g., by being asked about its presence. The following phase is therefore called divided-attention phase, because participants are now aware of the US and are expected to split their attention between the US and the main task. Finally, after the divided-attention phase, participants are requested to ignore the main task and respond to the US. This last phase is called full-attention phase (Mack & Rock, 1998).

Inattentional blindness is often discussed in the literature about the relationship between attention and consciousness (e.g., Kentridge, 2011; Lamme, 2003; Mole, 2008; Pitts et al., 2018), often to argue that attention is necessary for awareness (Prinz, 2011). In part, this is due to the large literature on the phenomenon, including a whole book written by the original proponents of the paradigm (Mack & Rock, 1998). More naturalistic versions of the paradigm have also been developed, such as the “gorillas in our midst” study (Simons & Chabris, 1999), leading to the popularization of the phenomenon of inattentional blindness (Chabris & Simons, 2010). Subsequent studies showed that inattentional blindness has high ecological validity and has important real-world implications (Chabris et al., 2011; Murphy & Greene, 2017; Simons, 2000).

Characteristics of the inattentional blindness distinguish it from the two other paradigms presented above and put it in a unique position to study the relationship between attention and awareness. In contrast to the attentional blink and change blindness, inattentional blindness does not rely on brief exposure times or flickers. Instead, a crucial factor for whether an observer is aware or unaware of a stimulus is expectation or previous knowledge of the stimulus (Braun, 2001; Mack & Rock, 1998; Ward & Scholl, 2015; White & Davies, 2008). This is shown by the observation that, in the overwhelming majority of inattentional blindness experiments**,** most participants become aware of the US after being questioned about it. Thus, in inattentional blindness, the crucial variable that determines whether a stimulus is noticed or not is top-down or voluntary attention. This allows for the study of the effects of attention on stimulus processing dissociated from stimulus-related variables.

Those differences are crucial because attention and stimulus factors are proposed to have distinct roles in the processing of noticed and unnoticed stimuli (Dehaene et al., 2014). Indeed, the differences in design of those paradigms imply distinct underlying mechanisms. Change blindness, for instance, involves perception of transitions between quantities (second-order information; Rensink, 2000). This requires manipulating information in and out of visual short-term memory (visual working memory) to compare inputs and detect changes. In contrast, inattentional blindness involves the perception of the presence of quantities (first-order information; Rensink, 2000) and does not require VSTM. Likewise, working memory has been shown to be involved in the attentional blink (Akyürek et al., 2007; Glennon et al., 2016). These differences suggest that distinct mechanisms are at work in inattentional blindness and those other paradigms (Rensink, 2010).

Inattentional blindness studies assume that attention is necessary for awareness; thus, if a participant’s attention is directed away from a US to an attentionally demanding task and the US cannot be reported, it is assumed to be unattended. However, absence of report of a stimulus does not imply that no processing of the stimulus occurred (Wood & Simons, 2019). Decades of investigation with priming (Berkovitch & Dehaene, 2019; Dehaene et al., 2001, 1998; Naccache & Dehaene, 2001), as well as experimental techniques such as continuous flash suppression (Chung & Khuu, 2014; Lin & Yeh, 2016; Mudrik et al., 2011) and masking (Giattino et al., 2018; Peremen & Lamy, 2014), have suggested that unreported stimuli nonetheless influence cognition. This influence may reach considerably high-levels, although some of the evidence for that claim has been disputed (e.g., Moors et al., 2016; Moors et al., 2019). Studies on this issue seek to employ measurements that can detect processing of stimuli even when they cannot be reported. In this paper, we use “unconscious” or “implicit” to refer to stimuli that are not reported by participants in an experimental task.

Although the original studies on inattentional blindness suggested that unreported US are not processed (e.g., Mack et al., 1992), most recent research has arrived at the opposite conclusion (e.g., Mack & Rock, 1998; Moore & Egeth, 1997; Pitts et al., 2012). To contribute to a synthesis of the results in this area, in the present study we review the empirical studies that investigate unconscious processing during inattentional blindness. We present a qualitative review of experimental designs and results from a meta-analytic review of effect sizes reflecting implicit processing.

An additional goal of this study concerns the investigation of the related issue of the adequacy of awareness tests employed to determine if stimuli are implicit. Vadillo et al. (2016) conducted a meta-analysis of 73 studies assessing the power of awareness tests in studies investigating implicit processing in contextual cueing paradigms. To conclude that a stimulus is processed implicitly, an assessment of awareness must exhibit null results in combination with significant results on a behavioral performance test. However, Vadillo et al. (2016) showed that, in many cases, such awareness assessments are actually underpowered to detect small effects of awareness.

Additionally, they observed that a large number of studies showed a significant effect in awareness tests, summing up to a proportion of 21.5%. That proportion is above the expected rate of 5% of false positives, assuming that the null hypothesis was false. Lastly, the meta-analytic effect size observed for the probability of awareness was significantly different from chance. Overall, although contextual cueing effects are robust (Chun & Jiang, 1998; Vadillo et al., 2016), the results of their meta-analysis do not support the conclusion that contextual cueing is implicit. Considering those results, it is reasonable to inquire if a similar issue occurs in studies on implicit processing during inattentional blindness. Hence, we also investigated whether the results of the awareness assessments in those studies support the conclusion that processing of the US is implicit.

Methods

Literature Search

We followed the PRISMA guidelines for the selection of papers (Moher et al., 2009). An automated search was conducted in the databases Web of Science, Scopus, PubMED, and PsycINFO, using the search term “inattentional blindness” in combination with the terms “implicit*”, “aware*” or “conscious*”. This search returned 805 papers. We complemented this automated search with a manual search of reference lists of review and empirical papers, as well as with a survey of the grey literature, which returned 14 additional papers. The resulting number of retrieved papers was 819, of which 415 repetitions were excluded. Our search was performed on 10 July 2020, with no start date.

In the next step, we screened the abstracts of the retained papers. Theoretical papers, reviews and studies on computational modeling were excluded, as they did not report any new behavioral or physiological results. Articles not written in English were also excluded. Conference presentations, theses, dissertations, and book chapters were selected for screening. This screening by abstracts excluded 285 papers not fitting the review’s aims. As an exception, we included one meta-analysis (Kreitz et al., 2020) suggested by one of the reviewers. This meta-analysis provides new data from the authors’ research group that had not been reported in the original studies. Since data for the individual papers is reported in Kreitz et al.’s (2020) meta-analysis, we included all of those which fitted the aims of the current review (these are counted among the manual search papers). This led to the exclusion of two papers from the 14 reported in Kreitz et al. (2020), both of which were cross-modal experiments, whereas the current review is restricted to the visual domain. The remaining 119 papers were fully read and evaluated with respect to fitting the review’s aims.

For screening of abstracts and evaluation of full texts, we adopted the following criteria to exclude experiments employing experimental paradigms that cannot be strictly characterized as inattentional blindness. First, attention misdirection experiments (e.g., Kuhn & Findlay, 2010) were excluded because, despite conceptual similarities, this paradigm differs in important ways from inattentional blindness, and the two have been argued to configure distinct phenomena (Memmert, 2010; Moran & Brady, 2010). Even though the precise mechanisms behind the two phenomena are still largely undetermined, and their definition has been a matter of debate (e.g., Kuhn & Tatler, 2011), several differences have been pointed out between them. One crucial point is that, in inattentional blindness, participants are not informed about the critical stimulus and have no expectation of it, while misdirection experiments use concomitant stimulation to direct attention away from the critical stimulus, and participants are initially informed about the concomitant stimuli. Considering the lack of consensus regarding the relationship between both paradigms, we believe that their differences suffice to warrant separate investigation of each phenomenon.

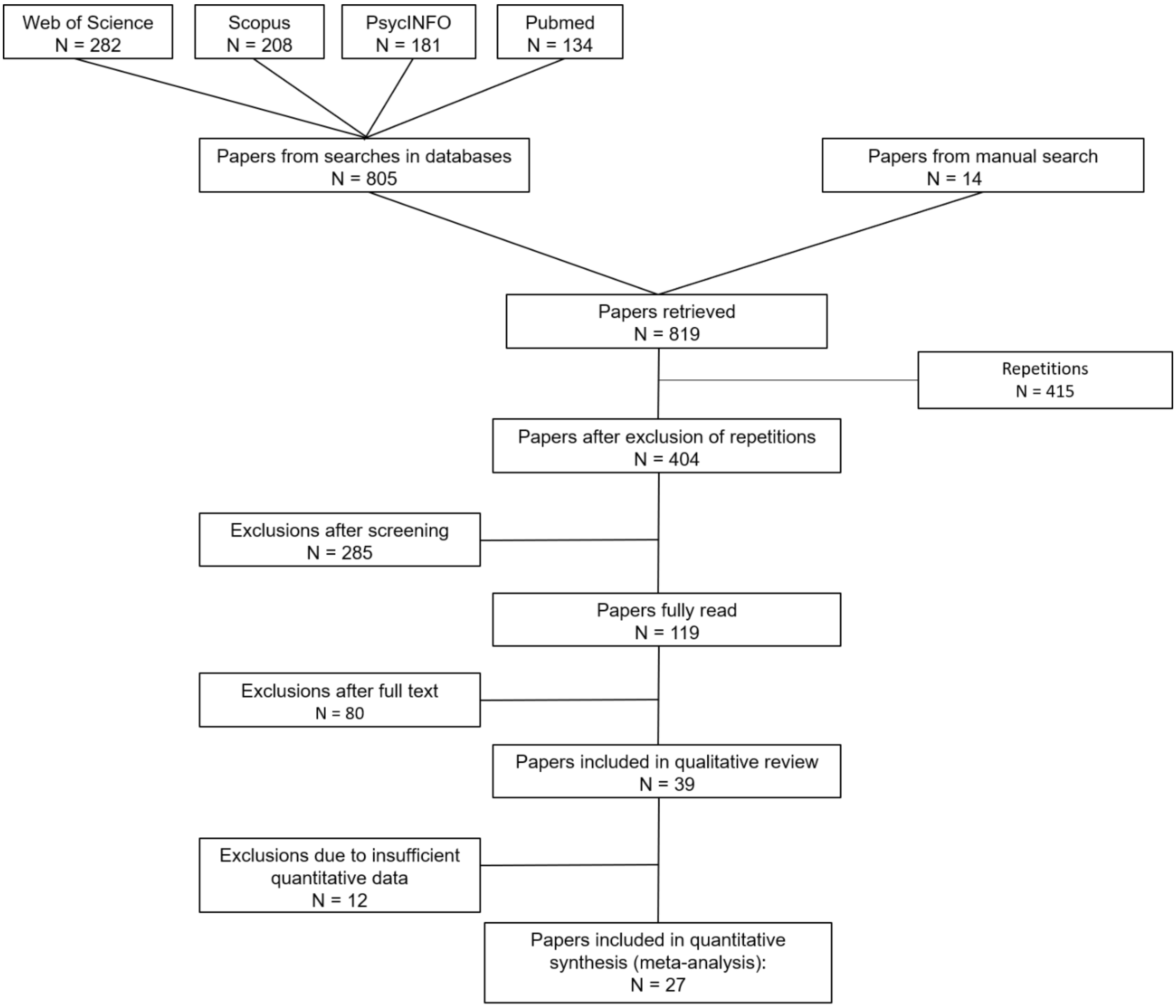
Dual-task experiments were also excluded. In this paradigm, participants are informed about two sets of stimuli/tasks but are instructed to ignore one of them; hence, the critical stimuli are not truly unexpected, just ignored. This leads to a greater likelihood that attention “leaks” to the distractor than in inattentional blindness, in which not informing participants in advance about the critical stimulus contributes to reduce the chance of such “leaking” (Scholte et al., 2006). Expectation of the critical stimulus may significantly modulate implicit processing, and lead to different implicit effects between the two designs. Indeed, dual-task designs are more similar to the divided-attention phase of inattentional blindness experiments, in which participants already know about the unexpected stimulus but are not required to attend to it.

We also excluded experiments in which the instructions mentioned the critical stimulus, even if they required participants to ignore it. We decided to exclude those experiments even though some still referred to such designs as inattentional blindness. Such choice was made based on the following observations: 1) inattentional blindness was explicitly created to eliminate voluntary attention from a perceptual situation; and 2) expectation is crucial feature of the inattentional blindness phenomenon, as shown by the generally large increase in noticing rates after the first awareness assessment. In contrast, when subjects are informed about the irrelevant stimulus, they may develop expectations about it, which may change the attentional dynamics of the critical stimulus. For example, it has been suggested that to-be-ignored stimuli are not excluded by attention; instead, they are initially attended and then suppressed (Cunningham & Egeth, 2016; Fukuda & Vogel, 2011).

These criteria were applied independently by the authors of the present study, with disagreements adjudicated by all authors. This led to the exclusion of 80 papers and 39 papers selected for the qualitative review. As many papers reported more than one experiment, these 39 papers encompassed a total of 72 experiments. From the 39 papers selected for the qualitative review, 12 papers were not included in the quantitative review: 9 due to the lack of behavioral data and 3 for not providing enough information to compute effect sizes. The final sample for the quantitative review consisted of 27 papers. One experiment was removed from one of the selected papers due to the absence of enough data to compute a summary effect size, leading to a total of 59 experiments in the quantitative analysis (we refer interchangeably to the experiments as “studies” in the remainder of the text). Of note, the paper by Most et al. (2005) comprised 7 experiments, which were pooled together by the authors in an eighth experiment investigating implicit processing across all experiments. A Cohen’s kappa of .77 was obtained, indicating a good agreement between raters (Cohen, 1960). Figure 3-1 depicts the paper selection process.

Figure 3-1

Paper selection flowchart



Coding

All studies were coded by both the first and second author, and each author’s coding was checked by the other. The articles were coded according to the following variables:

1. Main task: Type of behavioral task performed on which participants focused their attention during presentation of the US.
   Code: e.g. "letter tracking", "shape discrimination".
2. US relevance (implicit measure): Whether the US interacted with the stimuli in the main task, either by constituting part of the main stimuli or by forming a configuration with it. The US could be classified as relevant even if they were not mentioned in the instructions.
   Code: "irrelevant" or "relevant".
3. Modality (implicit measure): Modality of measure used to assess the implicit processing of the US.
   Code: "behavioral", "eye movements" or "EEG".
4. Static/dynamic: Whether the US was a static or moving stimulus.
   Code: “static”, “dynamic”.
5. Awareness testing method: How awareness of participants was assessed to select participants for investigation of implicit processing.
   Code: “post-hoc data selection” or “group assessment of awareness”.
6. Implicit measure: Measure used as dependent variable to quantify implicit processing.
   Code: "RT", "accuracy", "eye fixations" or "ERPs". When a study reported both reaction times (RTs) and accuracy, these were coded separately for the meta-analysis.
7. Online/offline: Whether implicit processing was assessed during the inattentional blindness task (when the US was present) or retroactively, after the US disappeared.
   Code: "online" or "offline".
8. N trials (implicit measurement): Number of trials used to assess implicit processing.
   Code: continuous number.
9. N participants (implicit measurement): Number of participants in the implicit processing measurement.
   Code: continuous number.
10. Awareness task: Type of task used as criterion to categorize participants’ awareness of the US.
    Code: "AFC discrimination", "yes-or-no detection", "cued recall", "free recall" or "confidence rating".

11. Objective/subjective (awareness measure): Whether participants' awareness was assessed using an objective measure of awareness (e.g. AFC) or subjective reports provided by participants about their own perceptual experience (e.g. confidence rating).
    Code: "objective", "subjective", or, when both were employed, "objective, subjective".
12. Delay (awareness measure): Whether the delay between the task and the assessment of awareness of the US was fixed or variable (i.e. according to a variable/random criterion or to subjects performance).
    Code: "fixed" or "variable".
13. N trials (awareness measure): Number of trials used to assess awareness.
    Code: continuous.
14. N participants (awareness measure): Number of participants in the awareness measurement.
    Code: continuous.

The results of the coding process are shown in Table 3-1. Since distinct experiments within the same study used distinct samples and methods, we chose to describe them in separate lines. Additionally, some papers (Beanland & Pammer, 2010; Kimchi et al., 2004; Lamy et al., 2006; Lo & Yeh, 2008; Razpurker-Apfeld and Pratt, 2008) report experiments that include multiple conditions, each investigating implicit processing with independent samples and distinct methods. In those cases, we describe each condition in a separate line of Table 3-1, as these are also analyzed as separate contrasts in the quantitative analysis.

Data Analysis

We estimated the meta-analytic effect size of implicit responses by comparisons of performance in trials with and without US presentation. We used correlations as measures of effect size, which has advantages over effect sizes based on standardized mean differences, such as Cohen's *d*, when studies with distinct degrees of freedom are combined (Rosenthal & DiMatteo, 2001). We computed *r* for each contrast from the means and standard deviations for each condition, when provided. In other cases, we used either *t*-values, *F*-values, or $\chi 2$ values to compute *r*. In a few cases, we converted *r* from the given value of Cohen's *d*. Since several studies included more than one experiment, each with a different sample, we computed separate effect sizes for each experiment. The same procedure was performed when an experiment investigated implicit processing in multiple experimental conditions each employing a distinct sample.

For results on implicit processing, effect sizes were coded as positive when the observed result was in the direction predicted if the US was implicitly processed, and negative otherwise. Several of the studies reported comparisons for both RT and accuracy. We computed effect sizes separately for each of those contrasts when the corresponding data were available. Because those effect sizes came from the same samples of participants, they were combined in a multi-level model. Some papers reported enough information to compute effect sizes for only one of those measures. In those cases, we computed the effect sizes for the measure with available data. This resulted in a total of 86 effect sizes for implicit processing.

For awareness effect sizes, we computed *r* from the proportion or percentage of participants who reported the US in each experiment. To standardize the sign of effect sizes, we compared the effect size to the number of participants that would be expected to provide correct responses if all participants responded randomly. For example, if the experiment uses a 4AFC to assess participants' awareness, a 25% rate of correct responses would be expected. Importantly, this is only relevant for experiments in which implicit processing is assessed for the whole sample, including both aware and unaware participants (group assessment of awareness). Therefore, we do not include in this analysis experiments that tested for implicit processing in a subgroup of participants considered unaware according to individual awareness results ("post-hoc data selection"). Moreover, awareness tests contributed only one result by experiment for both RT and accuracy contrasts. Therefore, the meta-analytic model for awareness included fewer contrasts than the model for implicit effects. In total, 35 contrasts were combined in this analysis.

We coded effects in the direction of "awareness" (i.e., more participants than what would be expected by chance noticed the US) as positive, and effects in the direction of "lack of awareness" (i.e., fewer participants than what would be expected by chance noticed the US) as negative.

Most studies included multiple measures of awareness, which often differed in sensitivity. In the majority of cases, participants first had to report if they noticed any additional stimuli or pattern in the critical trial (yes-or-no detection), and then were asked to identify that stimulus (e.g. forced-choice, free or cued recall). For most studies, rates of awareness were generally higher when only the first question was considered than when both were considered. We considered the use of only the first question as a "lax" criterion for assessing awareness, and the use of the two questions as a "strict" criterion, roughly corresponding to the definitions of Wood and Simons (2019). The results of the meta-analytic model for awareness effect sizes may change depending on which criterion is employed. To evaluate possible differences in rates of awareness due to the use of lax or strict measures, we built separate meta-analytic models using effect sizes for each criterion, when these were reported separately.

After computing all individual effect sizes, an analogous procedure was conducted for both implicit and awareness analyses. We built the model using Fisher's *z*-transformed correlations using the following formula (Borenstein et al., 2009):

$$z = 0.5 \times \ln\left(\frac{1+r}{1-r}\right) \qquad (1)$$

Where *z* is the Fisher's *z*-transformed value, ln is the natural logarithm, and *r* is the correlation value for the contrast.

We employed a random-effects model (Hunter & Schmidt, 2004), given that effect sizes were expected to vary in the population (Field & Gillett, 2010). Since several studies resulted in more than one effect size, we used a three-level model where the additional level refers to effect sizes for outcomes within the same study (Borenstein et al., 2009; Harrer et al., 2019). The formula for the model is given in equation 2:

$$\hat{\theta}_k = \beta_0 + \nu_k + \zeta_{ik} + \varepsilon_{ik} \qquad (2)$$

Where $\hat{\theta}_k$ is the θ observed effect size for study k; β_0 is the overall mean effect size; ν_k is the random deviation of the mean effect size of study k from the overall mean effect size; ζ_{ik} is the random deviation of the effect size for outcome i in study k from the mean effect in study k; and ε_{ik} is the random error due to sampling.

Heterogeneity in the effect sizes was initially assessed using τ^2, defined as the variance of the true effect sizes (Borenstein et al, 2009). Then, we examined the width of confidence intervals (CIs) in forest plots to search for studies with unusually large CIs and outlier studies, defined as those with 95% CIs falling outside the upper or lower bound of the 95% CI of the pooled effect size (Harrer et al., 2019).

A moderator analysis was conducted to explore the existence of subgroups among the studies. We analyzed subgroups clustered according to different criteria (e.g., type of response measures, number of trials). The specific variables used as criteria are described below. In the case of binary categorical variables, we re-ran the meta-analysis separately for each subgroup defined by the levels of the variable. In the case of continuous variables, we conducted a meta-regression including the variable as a predictor.

Results

Qualitative Review

The studies included in the review, along with their main features, are displayed in Table 3-1.

Table 3-1

Studies on Implicit Processing during Inattentional Blindness included in the qualitative review

Study	Main task		Implicit Measure						Awareness Measure						
	Task	Static/ dynamic	US relevance	Modality	Measure	Online/ offline	No trials	No parts	Awareness Task	Objective/ subjective	Delay	Awareness testing method	T. Assessment	No trials	No parts
*Ariga et al. (2007) - Exp. 2	Letter discrimination	Static	Relevant	Behavioral	RT	Online	1	20	Two 2-AFC tasks	Objective	Fixed	Group assessment	After CT	1	20
*Beanland and Pammer (2010) - Exp. 1A ("fixating" condition)	Letter tracking with bounce counting	Dynamic	Irrelevant	Behavioral	Accuracy	Online	2	27	Y/N, cued recall, 8-AFC	Objective	Fixed	Post-hoc data selection	After 2nd CT	1	72
*Beanland and Pammer (2010) - Exp. 1A ("moving" condition)	Letter tracking with bounce counting	Dynamic	Irrelevant	Behavioral	Accuracy	Online	2	31	Y/N, cued recall, 8-AFC	Objective	Fixed	Post-hoc data selection	After 2nd CT	1	72
*Beanland and Pammer (2010) - Exp. 2 ("fast US" condition)	Letter tracking with bounce counting	Dynamic	Irrelevant	Behavioral	Accuracy	Online	2	41	Y/N, cued recall, 8-AFC	Objective	Fixed	Post-hoc data selection	After 2nd CT	1	50
*Beanland and Pammer (2010) - Exp. 2 ("slow US" condition)	Letter tracking with bounce counting	Dynamic	Irrelevant	Behavioral	Accuracy	Online	2	41	Y/N, cued recall, 8-AFC	Objective	Fixed	Post-hoc data selection	After 2nd CT	1	50
Cheng et al. (2019)	Go/no-go with orientation discrimination	Static	Irrelevant	Behavioral	RT, Accuracy	Online	461	19	Y/N, cued recall, 6-AFC, CR, FR	Objective, subjective	Variable	Post-hoc data selection	After block	1	19
*Gabay et al. (2012) - Exp. 1	Line length judgement	Static	Relevant	Behavioral	RT	Online	72	18	Y/N, free recall	Objective	Variable	Post-hoc data selection	After block	40	30
*Gabay et al. (2012) - Exp. 2	Line length judgement	Static	Relevant	Behavioral	RT	Online	72	10	Y/N, free recall	Objective	Variable	Post-hoc data selection	After block	40	23
Harris et al. (2018)	Discrimination of number of patches	Static	Irrelevant	EEG	ERP	Online	380	47	Cued recall, free recall, 6-AFC,	Objective, subjective	Fixed	Post-hoc data selection	After block	1	47

									CR, FR						
*Kimchi and Peterson (2008) - Exp. 1	Same/different judgement	Static	Irrelevant	Behavioral	RT, accuracy	Online	160	46	Two 2-AFC	Objective	Variable	Group assessment	After block	1	46
*Kimchi et al. (2004) - Exp. 1 (“column/row by color” condition)	Same/different judgement	Static	Irrelevant	Behavioral	RT, accuracy	Online	160	14	Y/N, cued recall	Objective	Variable	Group assessment	After block	1	14
*Kimchi et al. (2004) - Exp. 1 (“triangle/arrow by color” condition)	Same/different judgement	Static	Irrelevant	Behavioral	RT, accuracy	Online	160	14	Y/N, cued recall	Objective	Variable	Group assessment	After block	1	14
*Kimchi et al. (2004) - Exp. 1 (“triangle/arrow” condition)	Same/different judgement	Static	Irrelevant	Behavioral	RT, accuracy	Online	160	14	Y/N, cued recall	Objective	Variable	Group assessment	After block	1	14
*Kimchi et al. (2004) – Exp. 1 (“connected triangle/arrow” condition)	Same/different judgement	Static	Irrelevant	Behavioral	RT, accuracy	Online	160	14	Y/N, cued recall	Objective	Variable	Group assessment	After block	1	14
*Kimchi et al. (2004) - Exp. 2 (“square/cross by color” condition)	Same/different judgement	Static	Irrelevant	Behavioral	RT, accuracy	Online	160	12	Y/N, cued recall	Objective	Variable	Group assessment	After block	1	12
*Kimchi et al. (2004) - Exp. 2 (“square/cross” condition)	Same/different judgement	Static	Irrelevant	Behavioral	RT, accuracy	Online	160	12	Y/N, cued recall	Objective	Variable	Group assessment	After block	1	12
*Kimchi et al. (2004) - Exp. 2 (“vertical/horizontal by color” condition)	Same/different judgement	Static	Irrelevant	Behavioral	RT, accuracy	Online	160	12	Y/N, cued recall	Objective	Variable	Group assessment	After block	1	12
*Kimchi et al. (2004) - Exp. 2 (“disconnected square/cross” condition)	Same/different judgement	Static	Irrelevant	Behavioral	RT, accuracy	Online	160	12	Y/N, cued recall	Objective	Variable	Group assessment	After block	1	12
*Kreitz et al. (2015a) - Exp. 1	Cross length judgment	Static	Irrelevant	Behavioral	Accuracy	Offline	1	69	Y/N, CR, 4-AFC, 6-AFC	Objective, subjective	Fixed	Post-hoc data selection	After CT	1	69
*Kreitz et al. (2015a) - Exp. 2	Object tracking with bounce counting (BC) + cross length judgment (LJ)	Static/ Dynamic	Irrelevant	Behavioral	Accuracy	Offline	1	86	Y/N, CR, 4-AFC, 6-AFC (BC) + Y/N, 5-AFC, 6-AFC (LJ)	Objective, subjective	Fixed	Post-hoc data selection	After CT	1	86
*Kreitz et al. (2015b) - Exp. 1	Lexical decision	Static	Irrelevant	Behavioral	Accuracy	Offline	1	62	Y/N, 4-AFC, 6-AFC, 5-AFC	Objective	Fixed	Post-hoc data selection	After CT	1	62

*Kreitz et al. (2015b) - Exp. 2	Letter detection	Static	Irrelevant	Behavioral	Accuracy	Offline	1	64	Y/N, 4-AFC, 6-AFC, 5-AFC	Objective	Fixed	Post-hoc data selection	After CT	1	64
*Kreitz et al. (2015b) - Exp. 3	Lexical creativity	Static	Irrelevant	Behavioral	Accuracy	Offline	1	38	Y/N, 4-AFC, 6-AFC, 5-AFC	Objective	Fixed	Post-hoc data selection	After CT	1	38
*Kreitz et al. (2015c)	Lexical decision	Static	Irrelevant	Behavioral	Accuracy	Offline	1	290	Y/N, 4-AFC, 5-AFC, 6-AFC	Objective	Fixed	Post-hoc data selection	After CT	1	290
*Kreitz et al. (2016a) - Exp. 1	Object tracking with bounce counting	Dynamic	Irrelevant	Behavioral	Accuracy	Offline	1	42	Y/N, 2-AFC, 5-AFC, 6-AFC	Objective	Fixed	Post-hoc data selection	After CT	1	42
*Kreitz et al. (2016a) - Exp. 2	Object tracking with bounce counting	Dynamic	Irrelevant	Behavioral	Accuracy	Offline	1	33	Y/N, 2-AFC, 5-AFC, 6-AFC	Objective	Fixed	Post-hoc data selection	After CT	1	33
*Kreitz et al. (2016a) - Exp. 3	Object tracking with bounce counting	Dynamic	Irrelevant	Behavioral	Accuracy	Offline	1	21	Y/N, 2-AFC, 5-AFC, 6-AFC	Objective	Fixed	Post-hoc data selection	After CT	1	21
*Kreitz et al. (2016b)	Object tracking with bounce counting	Dynamic	Irrelevant	Behavioral	Accuracy	Offline	1	34	Y/N, 2-AFC, 5-AFC, 6-AFC	Objective	Fixed	Post-hoc data selection	After CT	1	34
*Kreitz et al. (2018) - Exp 1	Cross length judgment	Static	Irrelevant	Behavioral	Accuracy	Offline	1	57	Y/N, 4-AFC, 6-AFC	Objective	Fixed	Post-hoc data selection	After CT	1	57
*Kreitz et al. (2018) - Exp 2	Object tracking with bounce counting	Static	Irrelevant	Behavioral	Accuracy	Offline	1	64	Y/N, 2-AFC, 7-AFC, 6-AFC	Objective	Fixed	Post-hoc data selection	After CT	1	64
*Lamy et al. (2006) - Exp. 2 (“same” condition)	Line length judgement	Static	Relevant	Behavioral	Accuracy	Online	16	8	Y/N, 4-AFC, CR	Objective, subjective	Variable	Post-hoc data selection	After CT	1	8
*Lamy et al. (2006) - Exp. 2 (“different” condition)	Line length judgement	Static	Relevant	Behavioral	Accuracy	Online	16	8	Y/N, 4-AFC, CR	Objective, subjective	Variable	Post-hoc data selection	After CT	1	8
*Lamy et al. (2006) - Exp. 3	Letter discrimination	Static	Irrelevant	Behavioral	RT, accuracy	Online	360	9	Y/N, 4-AFC	Objective	Variable	Post-hoc data selection	After CT	1	9
*Lamy et al. (2006) - Exp. 4	Letter discrimination	Static	Irrelevant	Behavioral	RT, accuracy	Online	360	9	Y/N, CR	Objective, subjective	Variable	Post-hoc data selection	After CT	1	9

*Lamy et al. (2006) - Exp. 5	Letter discrimination	Static	Irrelevant	Behavioral	RT, accuracy	Online	360	11	Y/N, CR	Objective, subjective	Variable	Post-hoc data selection	After CT	1	11
Lathrop et al. (2011)	Position recall and line length judgement	Static	Irrelevant	Behavioral	Accuracy	Online	1	53	Y/N, free recall	Objective	Fixed	Post-hoc data selection	500 ms	1	53
*Lo and Yeh (2008) - Exp. 1 (“200 ms” condition)	Line length judgement	Static	Relevant	Behavioral	Accuracy	Online	16	43	Y/N, 2-AFC, CR	Objective, subjective	Fixed	Group assessment	After CT	1	43
*Lo and Yeh (2008) - Exp. 1 (“500 ms” condition)	Line length judgement	Static	Relevant	Behavioral	Accuracy	Online	16	41	Y/N, 2-AFC, CR	Objective, subjective	Fixed	Group assessment	After CT	1	41
*Lo and Yeh (2008) - Exp. 2 (“200 ms” condition)	Line length judgement	Static	Irrelevant	Behavioral	RT	Online	64	23	Y/N, 2-AFC, CR	Objective, subjective	Fixed	Group assessment	After CT	1	23
*Lo and Yeh (2008) - Exp. 2 (“500 ms” condition)	Line length judgement	Static	Irrelevant	Behavioral	RT	Online	64	25	Y/N, 2-AFC, CR	Objective, subjective	Fixed	Group assessment	After CT	1	25
*Mack and Rock (1998) - Exp. 1	Line length judgement	Static	Irrelevant	Behavioral	Accuracy	Offline	1	50	Y/N, cued recall	Objective	Fixed	Post-hoc data selection	After CT	1	50
*Mack and Rock (1998) - Exp. 2	Line length judgement	Static	Irrelevant	Behavioral	Accuracy	Offline	1	41	Y/N, cued recall	Objective	Fixed	Post-hoc data selection	After CT	1	41
*Mack and Rock (1998) - Exp. 3	Line length judgement	Static	Irrelevant	Behavioral	Accuracy	Offline	1	21	Y/N, cued recall	Objective	Fixed	Post-hoc data selection	After CT	1	21
*Mack and Rock (1998) - Exp. 4	Line length judgement	Static	Irrelevant	Behavioral	Accuracy	Offline	1	29	Y/N, cued recall	Objective	Fixed	Post-hoc data selection	After CT	1	29
*Mack and Rock (1998) - Exp. 5	Line length judgement	Static	Irrelevant	Behavioral	Accuracy	Offline	1	19	Y/N, cued recall	Objective	Fixed	Post-hoc data selection	After CT	1	19
*Moore and Egeth (1997) - Exp. 1	Line length judgement	Static	Relevant	Behavioral	Accuracy	Online	16	20	Y/N, 2-AFC	Objective	Variable	Group assessment	After CT	1	20
*Moore and Egeth (1997) - Exp. 3	Line length judgement	Static	Relevant	Behavioral	Accuracy	Online	16	20	Y/N, 2-AFC	Objective	Variable	Group assessment	After CT	1	20
*Moore et al. (2003) - Exp. 3	Line discrimination	Static	Relevant	Behavioral	RT	Online	1	16	Y/N, 2-AFC, 2-AFC	Objective	Fixed	Group assessment	After CT	1	16

*Moore et al. (2004)	Letter discrimination	Static	Irrelevant	Behavioral	RT	Online	1	25	Y/N, 2-AFC, 2-AFC	Objective	Fixed	Group assessment	After CT	1	25
*Most et al. (2005) - Exp. 8	Object tracking with bounce counting	Dynamic	Irrelevant	Behavioral	Accuracy	Online	1	186	Y/N, free recall, cued recall	Objective	Fixed	Post-hoc data selection	After CT	1	370
*Nobre et al. (2020)	Contrast detection	Static	Irrelevant	EEG	ERP	Online	240	13	Y/N, free recall, CR, FR	Objective, subjective	Variable	Post-hoc data selection	Undetermi-ned (1 to 60 trials)	1	30
Pammer and Blink (2018)	Object tracking with bounce counting	Dynamic	Irrelevant	Behavioral	Accuracy	Online	1	71	Y/N, cued recall	Objective	Fixed	Group assessment	After CT	1	71
Pitts et al. (2011)	Contrast detection	Static	Irrelevant	EEG	ERPs	Online	240	16	Y/N, free recall, CR, FR	Objective, subjective	Variable	Post-hoc data selection	Undetermi-ned (1 to 60 trials)	1	32
*Pugnaghi et al. (2019)	Number categorization	Static	Irrelevant	Behavioral	Appeal, liking, familiarity	Online	220	201	Y/N, free recall, PR	Objective, subjective	Variable	Post-hoc data selection	After block	1	201
*Pugnaghi et al. (2020) – Exp. 1	Number categorization	Static	Irrelevant	Behavioral	RT, accuracy	Online	160	65	Y/N, free recall, FR	Objective	Variable	Post-hoc data selection	After block	1	76
*Pugnaghi et al. (2020) – Exp. 2	Number categorization	Static	Irrelevant	Behavioral	RT, accuracy	Online	160	102	Y/N, free recall, FR	Objective	Variable	Post-hoc data selection	After block	1	106
*Rashal et al. (2017) - Exp. 1	Same/different judgement	Static	Irrelevant	Behavioral	RT, accuracy	Online	160	20	2-AFC (twice)	Objective	Variable	Group assessment	After block	1	20
*Rashal et al. (2017) - Exp. 2	Same/different judgement	Static	Irrelevant	Behavioral	RT, accuracy	Online	160	28	2-AFC (three times)	Objective	Variable	Group assessment	After block	1	28
*Rashal et al. (2017) - Exp. 3	Same/different judgement	Static	Irrelevant	Behavioral	RT, accuracy	Online	160	18	2-AFC (twice)	Objective	Variable	Group assessment	After block	1	18
*Rashal et al. (2017) - Exp. 4	Same/different judgement	Static	Irrelevant	Behavioral	RT, accuracy	Online	160	15	2-AFC (twice)	Objective	Variable	Group assessment	After block	1	15

*Rashal et al. (2017) - Exp. 5	Same/different judgement	Static	Irrelevant	Behavioral	RT, accuracy	Online	160	18	2-AFC (twice)	Objective	Variable	Group assessment	After block	1	18
*Rashal et al. (2017) - Exp. 6	Same/different judgement	Static	Irrelevant	Behavioral	RT, accuracy	Online	160	18	2-AFC (twice)	Objective	Variable	Group assessment	After block	1	18
*Razpurker-Apfeld and Pratt (2008) – “columns/rows” condition	Visual shape discrimination	Static	Irrelevant	Behaviora, EEG	RT, accuracy, ERPs	Online	320	14	Y/N, cued recall	Objective	Variable	Group assessment	After block	1	14
*Razpurker-Apfeld and Pratt (2008) – “triangle/arrow” condition	Visual shape discrimination	Static	Irrelevant	Behaviora, EEG	RT, accuracy, ERPs	Online	320	14	Y/N, cued recall	Objective	Variable	Group assessment	After block	1	14
*Redlich et al. (2019) - Exp 1	Cross length judgment	Static	Irrelevant	Behavioral	Accuracy	Offline	1	68	Y/N, 4-AFC, 6-AFC	Objective	Fixed	Post-hoc data selection	After CT	1	68
*Redlich et al. (2019) - Exp 2	Object tracking with bounce counting	Dynamic	Irrelevant	Behavioral	Accuracy	Offline	1	178	Y/N, 4-AFC, 6-AFC	Objective	Fixed	Post-hoc data selection	After CT	1	178
Richards et al. (2012)	Object tracking with bounce counting	Dynamic	Irrelevant	Eye movement	Eye fixations	Online	1	131	Y/N, free recall	Objective	Not reported	Post-hoc data selection	After session	1	131
*Russell and Driver (2005) - Exp. 1	Same/different judgement	Static	Irrelevant	Behavioral	RT, accuracy	Online	480	25	Y/N, 2-AFC	Objective	Variable	Group assessment	After CT	1	25
*Russell and Driver (2005) - Exp. 2	Same/different judgement	Static	Irrelevant	Behavioral	RT, accuracy	Online	480	28	Y/N, 2-AFC	Objective	Variable	Group assessment	After CT	1	28
*Russell and Driver (2005) - Exp. 3	Same-different judgement	Static	Irrelevant	Behavioral	RT, accuracy	Online	600	24	Y/N, 2-AFC	Objective	Variable	Group assessment	After CT	1	24
*Russell and Driver (2005) - Exp. 4A	Same/different judgement	Static	Irrelevant	Behavioral	Accuracy	Online	600	20	2-AFC	Objective	Variable	Group assessment	After CT	1	20
*Russell and Driver (2005) - Exp. 4B	Same/different judgement	Static	Irrelevant	Behavioral	Accuracy	Online	600	20	Y/N	Objective	Variable	Group assessment	After CT	1	20
*Russell and Driver (2005) - Exp. 5	Same/different judgement	Static	Irrelevant	Behavioral	RT, accuracy	Online	600	24	Y/N, 2-AFC	Objective	Variable	Group assessment	After CT	1	24

Schelonka et al. (2017)	Contrast detection	Static	Irrelevant	EEG	ERP	Online	440	46	Free recall, 5-AFC, CR	Objective, subjective	Fixed	Post-hoc data selection	After block	1	46
*Schnuerch et al. (2016) - Exp. 1	Number categorization	Static	Irrelevant	Behavioral	RT	Online	100	61	Y/N, free recall	Objective	Variable	Post-hoc data selection	After phases	1	61
*Schnuerch et al. (2016) - Exp. 2	Number categorization	Static	Irrelevant	Behavioral	RT	Online	128	58	Y/N, free recall	Objective	Variable	Post-hoc data selection	After phases	1	58
Scholte et al. (2006) – MEG experiment	Letter covert identification	Static	Irrelevant	MEG	MEG activity	Online	225	14	2-AFC	Objective	Not reported	Post-hoc data selection	Not reported	1	14
Scholte et al. (2006) – fMRI experiment	Letter discrimination	Static	Irrelevant	fMRI	BOLD response	Online	225	14	9-AFC	Objective	Not reported	Post-hoc data selection	Not reported	1	14
Schlossmacher et al. (2020)	Contrast detection	Static	Irrelevant	EEG	ERP	Online	210	52	Y/N, cued recall, CR, FR	Objective, subjective	Variable	Post-hoc data selection	After phases	1	52
Shafto and Pitts (2015)	Contrast detection	Static	Irrelevant	EEG	ERP	Online	216	15	Y/N, cued recall, CR, FR	Objective, subjective	Variable	Post-hoc data selection	After phases	1	30
Vandenbroucke et al. (2014)	2-back in RSVP	Static	Irrelevant	fMRI	BOLD response	Online	72	37	8-AFC	Objective	Variable	Post-hoc data selection	After run	1	37
Wiemer et al. (2013)	Line length judgement	Static	Irrelevant	SCR	SCRs	Online	1	120	Y/N, free recall	Objective	Variable	Post-hoc data selection	4800 ms + RT	1	120
*Wood and Simons (2019) - Exp. 1	Line length judgement	Static	Relevant	Behavioral	Accuracy	Online	1	175	6-AFC, CR	Objective, subjective	Fixed	Post-hoc data selection	After CT	1	175
*Wood and Simons (2019) - Exp. 2	Line length judgement	Static	Irrelevant	Behavioral	Accuracy	Offline	1	216	Y/N, 5-AFC, CR	Objective, subjective	Fixed	Post-hoc data selection	After CT	1	216

Note. Studies preceded by an asterisk (“*”) are included in the quantitative analysis. US = unexpected stimulus; T. assessment = moment of assessment of awareness during the experiment; No trials = Number of trials in which assessment occurred; No parts = number of participants included in the assessment; RT = reaction time; Y/N = yes-or-no detection; EEG = electroencephalography; ERP = event-related potentials; CR

= confidence rating; FR = frequency rating; PR = preference rating; MEG = magnetoencephalography; fMRI = functional magnetic resonance imaging; BOLD = blood-oxygen-level-dependent; SCRs = skin conductance responses, CT = critical trial.

Assessment of Implicit Processing.

Behavioral Measures.

Most studies evaluated implicit processing by means of behavioral effects of interference caused by the US in main task performance. A common approach was to investigate whether the unnoticed US captured attention implicitly. For example, Most et al. (2005) conducted seven experiments using a dynamic inattentional blindness task, in which participants counted the bounces of moving stimuli and, in the critical trial, a US crossed the screen. The authors pooled together the participants of these seven experiments in an eight study to investigate implicit processing across all experiments. Participants unaware of the US showed an overall decrease in performance in the critical trial compared to the preceding trial in which no US was presented, suggesting implicit shifts of attention to the US. In contrast, no decrement in performance was observed in a control experiment that did not include a US.

Adaptations of the general procedure of Most et al. (2005) were used in other studies (Beanland & Pammer, 2010; Richards et al., 2012; Pammer & Blink, 2018). Together, these studies present evidence of exogenous orientation of attention by unconscious stimuli. On the other hand, the results of Gabay et al. (2012), which show an implicit top-down orientation of attention induced by unreported arrows, suggest that attention can also be oriented endogenously by the US.

Among the reviewed studies, a class of processes commonly examined are Gestalt grouping and figure-ground segmentation. In an influential study, Moore and Egeth (1997) conducted two experiments to investigate if perceptual grouping occurs during inattentional blindness. The display was composed of two lines presented in the center among background dots configuring Ponzo (experiment 1) or Müller-Lyer (experiment 3) illusions in critical trials, while participants had to discriminate the length of the lines. Results showed that background configuration interfered with the task: identical lines appeared to have different lengths when the background was configured so as to elicit the illusions, even though the configurations of the dots were never consciously perceived.

Moore and Egeth’s (1997) findings of perceptual grouping under inattention have been replicated by Lamy et al. (2006), using the Müller-Lyer illusion, and more recently by Wood and Simons (2019), using both the Müller-Lyer and Ponzo illusions. Lo and Yeh (2008) also used the Ponzo illusion to evaluate implicit texture segregation during inattentional blindness and found converging evidence. Employing a different illusion - the Roelofs effect - Lathrop et al. (2011) reported an effect of spatial mislocalization of targets induced by an unreported frame, in that participants mislocalized target positions as if they had processed the surrounding frame.

Other studies employed similar designs to investigate other Gestalt processes. For example, Moore et al. (2003) used modal and amodal completion as a measure of implicit processing. In their design, a visual display showed either a solid line or a dashed line alongside background pacmen stimuli in the background. The pacmen stimuli could be aligned so as to induce the formation of an illusory rectangle through surface completion; this illusory rectangle was the US. Even though participants were inattentionally blind to the modally-completed rectangle, responses were slower to dashed lines when this rectangle occluded the gaps in the line compared to when the pacmen stimuli were not aligned and thus did not configure a triangle. This suggests that surface completion can be triggered by unattended stimuli (i.e., the pacmen stimuli).

Similar stimuli were employed by Ariga et al. (2007) to investigate the same-object advantage (Egly et al., 1994), which refers to a reduction in RTs to invalidly-cued stimuli that belong to the same object compared to stimuli belonging to a distinct object. In this study, unattended pacmen stimuli unexpectedly configured illusory objects, which were used to elicit a same-object advantage. Although such an effect was found when participants were aware of the objects formed by the pacmen, the same was not observed for inattentionally blind participants.

Effects of contour integration were investigated by Cheng et al. (2019) using a modified inattentional blindness paradigm with varying levels of perceptual load. They reported a modulatory effect of perceptual load in contour integration which depended on consciousness. In conditions of low perceptual load, only salient circles were successfully integrated during inattentional blindness, while both salient circles and S-contours could be integrated consciously.

Perceptual grouping under conditions of inattention has also been examined by studies using the ‘inattention paradigm” (Kimchi & Razpurker-Apfeld, 2004; Russell & Driver, 2005; Razpurker-Apfeld & Pratt, 2008; Kimchi & Peterson, 2008; Rashal et al., 2017). This paradigm differs in some aspects from the typical inattentional blindness design, but follows the same fundamental structure. The inattention paradigm evaluates the effect of changing the configuration of background stimuli on the detection of small changes in a target matrix presented at the center of the screen, compared to a condition in which the background stays the same (see the “Inattention Paradigm” section). Using various configurations of background elements, these studies have generally observed that some types of grouping occurs implicitly under inattention. Furthermore, results from several of those studies suggest that attentional demands differ between perceptual organization processes.

Another type of process that has been investigated under inattentional blindness is response selection. Two studies (Moore et al., 2004; Lo & Yeh, 2008) used similar designs based on a stimulus-response compatibility effect: the Simon effect (Simon & Rudell, 1967). This effect consists in the fact that participants respond faster when a task-irrelevant stimulus (e.g. a square) appears on the same side as the correct response, compared to when it appears on the opposite side. In conditions in which the irrelevant stimulus was unattended, both studies found no effects of interference on performance, suggesting that response-selection processes do not occur under inattention.

Other processes, such as semantic processing, have also been examined in the context of inattentional blindness. Schnuerch et al. (2016) used a number categorization task in which participants had to respond whether a target number presented in the periphery of the screen was smaller or greater than 5. The center of the screen was composed of a distractor array irrelevant to the main task. When the array contained numbers that matched the target, responses were faster than when it contained non-matching numbers. This basic effect was replicated by Pugnaghi et al. (2020) in a design modified to manipulate perceptual load.

In contrast to studies which evaluated implicit processing with online interference measures, Mack and Rock (1998) reported a series of studies using offline measures. These studies used essentially the same design as the original inattentional blindness experiments (Mack et al., 1992; Rock et al., 1992), but included an additional task administered after the critical trial to measure implicit processing; specifically, stem-completion tasks and recognition tests. They observed, similarly to earlier studies on auditory attention (e.g., Bentin et al., 1995), that unattended stimuli are semantically processed even when unnoticed. A study by Wood and Simons (2019) attempted to replicate this word-stem priming effect, but found no converging evidence.

Using the same paradigm as Schnuerch et al. (2016), Pugnaghi et al. (2019) explored possible effects of mere exposure to preconscious stimuli in the array (nonwords or Chinese symbols) in an offline assessment of preference. However, no mere exposure effects were observed; hence, no processing of preconscious stimuli was inferred. Moreover, a recent meta-analysis investigated preconscious processing in inattentional blindness employing offline measures (Kreitz et al., 2020), in which the authors reanalyzed 16 datasets from studies originally designed to investigate different research questions. The meta-analysis analyzed participants’ accuracy in multiple-choice questions about the US and found above-chance guessing accuracy when participants could not report the US, suggesting preconscious processing of the stimuli.

Psychophysiological and Eye-Tracking Measures.

Some studies have employed other types of measures to investigate implicit processing of the US in addition to the main behavioral task. These include eye-tracking, skin-conductance responses (SCRs), electroencephalography (EEG), functional magnetic resonance imaging (fMRI), and magnetoencephalography (MEG).

Eye-tracking studies usually evaluate implicit processing by examining if inattentionally blind participants fixate a US. Results from Beanland and Pammer (2010) show that both noticers and nonnoticers were equally likely to make saccades toward the US, suggesting that the US covertly captures attention and attracts eye movements independently of participants' awareness. Richards et al. (2012) found that nonnoticers fixated the US less frequently and later in the task compared to noticers. Some inattentionally blind participants appeared to fixate the US but failed to report it, although they might have attended the US covertly. Using SCRs combined with eye-tracking, Wiemer et al. (2013) found converging results with both measures. An arousing US (a spider) elicited higher SCRs and was fixated more often than a neutral US (a flower), even though both stimuli were reported equally often.

Another group of studies used EEG to investigate implicit processing of US during inattentional blindness. Pitts et al. (2012) recorded ERPs in response to the US in multiple critical trials while participants performed a contrast detection task. In their design, the US was a square contour formed by random line segments presented on the background, which were irrelevant to the main task. They found a difference between random and square configurations in a visual ERP component related to texture segregation in inattentionally blind participants.

Shafto and Pitts (2015) employed the same design, with the modification that the line segments in the background sometimes configured a face, used as US. Contrary to Pitts et al. (2012), no significant differences in ERPs between faces and random configurations were observed in inattentionally blind participants. Finally, in Schelonka et al. (2017), the background US configured words, and ERP results indicated early, implicit processing of those words. Other EEG studies were based on the design of Pitts et al. (2012), using geometrical configurations to investigate neural responses associated with stimulus awareness, such as Schlossmacher et al. (2020), evaluating ERP’s, and Harris et al. (2018), evaluating oscillatory activity. Those experiments focused on differences in ERPs between trials with and without a US, and did not compare performance in the main task between those conditions.

Finally, fMRI and MEG recordings were employed by some studies to identify neural signatures of implicit processing during inattentional blindness. In general, results revealed similar patterns of neural responses to the US between participants that were aware and those who were unaware of the stimulus for both scene segmentation (Scholte et al., 2005) and the Kanizsa figure illusion (Vandenbroucke et al., 2014).

Assessment of awareness.

Regarding the tasks employed to assess awareness, most experiments included more than one task (see Table 3-1). Often, both a less demanding task (e.g., a yes/no question asking participants if they saw anything besides the main task stimuli) and a more demanding one (e.g., asking participants to describe what they saw) were used. However, in some experiments (e.g., Rashal et al., 2017) multiple similar tasks were employed, such as a forced-choice questions about the organization (columns vs. rows) or shapes (squares vs. circles) formed by the background stimuli.

Some papers reported the number of aware participants for each measure separately (Kimchi & Razpurker-Apfeld, 2004; Moore et al., 2004; Razpuker-Apfeld & Pratt, 2008). Others reported only the number of participants that were considered aware in more than one measure (e.g., reporting seeing something besides the the main task stimuli *and* being able to describe it), instead of describing performance separately in each measure (Gabay et al., 2012; Lo & Yeh, 2008; Mack & Rock, 1998; Most et al., 2005; Schnuerch et al., 2016). A small number of papers reported both the results for each measure separately and the number of aware participants considering all measures (Beanland & Pammer, 2010; Wood & Simons, 2019).

In the majority of cases, awareness was measured only once with each measure, i.e., subjects responded to each question only once. When more assessments were performed, this was done using non-behavioral measures such as ERPs or SCRs in addition to the behavioral measures. In those studies, however, the criteria for categorizing participants as aware or unaware was a behavioral measure, with non-behavioral measures being employed with other objectives, such as identifying neural correlates of awareness (e.g., Pitts et al, 2012).

All studies administered awareness measures for each participant individually. However, they differed in how the results of those assessments were used to select participants for statistical testing of implicit processing effects. Some studies used awareness measures to perform post-hoc selection of a subset of unaware participants, who were then tested for implicit processing of the US separately from other participants. Other studies analyzed participants as a group, testing if the group perceived the US more than would be expected by chance. Then, the whole group was tested for implicit processing.

We also observed differences regarding objective and subjective measures of awareness (Seth et al., 2008). Objective measures assess awareness by the performance on specific tasks that allow to verify mismatches between stimuli and responses (Schmidt & Vorberg, 2006), such as 2-alternative forced-choice (2-AFC) recognition tasks. Subjective measures, on the other hand, rely on participants' report of their own mental states; examples include confidence ratings and the perceptual awareness scale (Sandberg et al., 2011).

Of the 72 experiments included in our review, 17 combined objective and subjective measures and 55 used only objective measures. None of the studies used only subjective measures. The majority of studies (n = 56) employed yes-or-no detection questions as objective measures. Forced-choice and free/cued recall questions were also used. Most of the studies (n = 67) used more than one task. Although most of the time results for all tasks were reported, it was rarely the case (n = 6; Most et al., 2005; Schnuerch et al., 2016, both experiments; Pitts et al., 2012; Shafto & Pitts, 2015; Schelonka et al., 2017) that more than one task was considered to categorize participants as aware or unaware (for studies using post-hoc data selection) or to determine that awareness was not above chance in a sample.

The subjective measures employed were mainly confidence (n = 18), frequency (n = 8) ratings, and preference ratings (n = 1). Of the experiments using subjective measures, four (Harris et al., 2018; Pitts et al., 2012; Shafto & Pitts, 2015; Schelonka et al., 2017) used those measures to categorize participants as aware or unaware. The remaining experiments (Lo & Yeh, 2008, experiments 1 and 2) classified participants using objective measures, employing the subjective measures to compare confidence between the inattention and divided-attention phases.

Quantitative Review (Meta-Analysis)

Overall meta-analytic results.

Table 3-2 reports Fisher’s *z* correlation values and standard errors for effect sizes included in the meta-analysis.

Table 3-2

Effect sizes estimates and standard errors for implicit processing measurements and awareness assessments of experiments included in the meta-analysis

Study	Implicit processing				Awareness assessment			
					Lax		Strict	
	Measure	*z*	SE(*z*)	Sig.	*z*	SE(*z*)	*z*	SE(*z*)
Ariga et al. (2007) - Exp. 2	RT	-0.14	0.24	No	0.10	0.24	0.00	0.24
Beanland and Pammer (2010) - Exp. 1A (“fixating” condition)	Accuracy	0.6	0.2	Yes	-	-	-	-
Beanland and Pammer (2010) - Exp. 1A (“moving” condition)	Accuracy	0.97	0.19	Yes	-	-	-	-
Beanland and Pammer (2010) - Exp. 2 (“fast US” condition)	Accuracy	0.37	0.16	No	-	-	-	-
Beanland and Pammer (2010) - Exp. 2 (“slow US” condition)	Accuracy	0.48	0.16	No	-	-	-	-
Gabay et al. (2012) - Exp. 1	RT	0.45	0.26	Yes	-	-	-	-
Gabay et al. (2012) - Exp. 2	RT	0.44	0.38	Yes	-	-	-	-
Kimchi and Peterson (2008) - Exp. 1	RT	0.39	0.15	Yes	0	0.15	0.09	0.15
	Accuracy	0.36	0.15	Yes				
Kimchi et al. (2004) - Exp. 1 (“column/row by color” condition)	RT	0.97	0.3	Yes	1.28	0.3	3.80	0.30
Kimchi et al. (2004) - Exp. 1 (“triangle/arrow by color” condition)	RT	-0.44	0.3	No	3.8	0.3	3.80	0.30
Kimchi et al. (2004) - Exp. 1 (“triangle/arrow” condition)	Accuracy	0.47	0.3	No	0.65	0.3	1.28	0.30
Kimchi et al. (2004) – Exp. 1 (“connected triangle/arrow” condition)	RT	1.24	0.3	Yes	1.28	0.3	1.28	0.30
	Accuracy	0.8	0.3	Yes				
Kimchi et al. (2004) - Exp. 2 (“square/cross by color” condition)	Accuracy	-0.4	0.33	No	3.8	0.33	3.80	0.33
Kimchi et al. (2004) - Exp. 2 (“square/cross” condition)	RT	0.7	0.33	No	3.8	0.33	3.80	0.33
	Accuracy	1.2	0.33	No				
Kimchi et al. (2004) - Exp. 2 (“disconnected square/cross” condition)	RT	1.01	0.33	Yes	1.2	0.33	0.55	0.33
	Accuracy	1.45	0.33	Yes	-	-	-	-
Kreitz et al. (2015a) – Exp. 1	Accuracy	0.06	0.12	Yes	-	-	-	-

Study	Implicit processing				Awareness assessment			
					Lax		Strict	
	Measure	*z*	SE(*z*)	Sig.	*z*	SE(*z*)	*z*	SE(*z*)
Kreitz et al. (2015a) – Exp. 2.1	Accuracy	0.24	0.11	Yes	-	-	-	-
Kreitz et al. (2015a) – Exp. 2.2	Accuracy	0.26	0.11	Yes	-	-	-	-
Kreitz et al. (2015b) – Exp. 1	Accuracy	0.09	0.13	Yes	-	-	-	-
Kreitz et al. (2015b) – Exp. 2	Accuracy	0.02	0.13	No	-	-	-	-
Kreitz et al. (2015b) – Exp. 3	Accuracy	0.05	0.17	No	-	-	-	-
Kreitz et al. (2015c)	Accuracy	0.05	0.06	Yes	-	-	-	-
Kreitz et al. (2016a) – Exp. 1	Accuracy	0.18	0.16	Yes	-	-	-	-
Kreitz et al. (2016a) – Exp. 2	Accuracy	0.20	0.18	Yes	-	-	-	-
Kreitz et al. (2016a) – Exp. 3	Accuracy	0.20	0.24	Yes	-	-	-	-
Kreitz et al. (2016b)	Accuracy	0.02	0.18	No	-	-	-	-
Kreitz et al. (2018) – Exp. 1	Accuracy	0.01	0.14	No	-	-	-	-
Kreitz et al. (2018) – Exp. 2	Accuracy	0.02	0.19	No	-	-	-	-
Lamy et al. (2006) - Exp. 2 (“same” condition)	Accuracy	0.55	0.45	Yes	0.39	0.45	0.39	0.45
Lamy et al. (2006) - Exp. 2 (“different” condition)	Accuracy	0.26	0.45	Yes				
Lamy et al. (2006) - Exp. 3	RT	0.97	0.41	Yes	0.35	0.41	0.35	0.41
Lamy et al. (2006) - Exp. 4	RT	1.33	0.41	Yes	0.80	0.41	0.80	0.41
Lamy et al. (2006) - Exp. 5	RT	0.90	0.35	Yes	1.24	0.35	1.24	0.35
Lo and Yeh (2008) - Exp. 1 (“200 ms” condition)	Accuracy	0.12	0.16	No	0.21	0.16	0.21	0.16
Lo and Yeh (2008) - Exp. 1 (“500 ms” condition)	Accuracy	0.67	0.16	Yes	0.02	0.16	0.02	0.16
Lo and Yeh (2008) - Exp. 2 (“200 ms” condition)	RT	0.36	0.22	No	-0.04	0.22	-0.04	0.22
Lo and Yeh (2008) - Exp. 2 (“500 ms” condition)	RT	0.00	0.21	No	-0.12	0.21	-0.12	0.21
Mack and Rock (2000) - Exp. 1	Accuracy	0.35	0.15	Yes	-	-	-	-
Mack and Rock (2000) - Exp. 2	Accuracy	0.42	0.16	Yes	-	-	-	-
Mack and Rock (2000) - Exp. 3	Accuracy	0.30	0.24	Yes	-	-	-	-
Mack and Rock (2000) - Exp. 4	Accuracy	0.40	0.20	Yes	-	-	-	-
Mack and Rock (2000) - Exp. 5	Accuracy	0.30	0.25	Yes	-	-	-	-
Moore and Egeth (1997) - Exp. 1	Accuracy	0.69	0.24	Yes	-1.10	0.24	-1.10	0.24
Moore and Egeth (1997) - Exp. 3	Accuracy	1.10	0.24	Yes	-3.80	0.24	-3.80	0.24
Moore et al. (2003) - Exp. 3	RT	0.40	0.28	Yes	0.09	0.28	0.09	0.28
Moore et al. (2004)	RT	0.10	0.21	Yes	-0.83	0.21	-0.04	0.21
Most et al. (2005) – Exp. 8	Accuracy	0.21	0.07	Yes	-	-	-	-
Nobre et al. (2020)	RT	0.15	0.31	No	-	-	-	-

Study	Implicit processing				Awareness assessment			
					Lax		Strict	
	Measure	*z*	SE(*z*)	Sig.	*z*	SE(*z*)	*z*	SE(*z*)
Pugnaghi et al. (2019)	Accuracy	0.13	0.07	No	-	-	-	-
Pugnaghi et al. (2020) – Exp. 1	RT	0.34	0.13	Yes	-	-	-	-
	Accuracy	0.34	0.13	Yes	-	-	-	-
Pugnaghi et al. (2020) – Exp. 2	RT	0.10	0.10	No	-	-	-	-
	Accuracy	0.20	0.10	Yes	-	-	-	-
Rashal et al. (2017) - Exp. 1	RT	0.61	0.24	Yes	0.10	0.24	0.10	0.24
Rashal et al. (2017) - Exp. 2	Accuracy	-0.26	0.20	Yes	0.14	0.20	0.14	0.20
Rashal et al. (2017) - Exp. 3	RT	0.30	0.26	No	0.23	0.26	0.23	0.26
Rashal et al. (2017) - Exp. 4	Accuracy	0.74	0.29	No	-0.07	0.29	-0.07	0.29
	RT	0.69	0.29	Yes				
Rashal et al. (2017) - Exp. 5	Accuracy	0.52	0.26	Yes	0.00	0.26	0.00	0.26
	RT	0.44	0.26	Yes				
Rashal et al. (2017) - Exp. 6	Accuracy	0.34	0.26	No	0.23	0.26	0.23	0.26
	RT	0.32	0.26	No				
Razpurker-Apfeld and Pratt (2008) – “columns/rows” condition	RT	0.61	0.30	Yes	3.80	0.30	-0.90	0.30
	Accuracy	0.58	0.30	Yes				
Razpurker-Apfeld and Pratt (2008) – “triangle/arrow” condition	RT	-0.01	0.30	Yes	3.80	0.30	-0.90	0.30
	Accuracy	0.41	0.30	Yes				
Redlich et al. (2019) – Exp. 1	Accuracy	0.02	0.12	No	-	-	-	-
Redlich et al. (2019) – Exp. 2	Accuracy	0.01	0.08	No	-	-	-	-
Russell and Driver (2005) - Exp. 1	Accuracy	0.87	0.21	Yes	-0.04	0.21	-0.04	0.21
	RT	0.39	0.21	No				
Russell and Driver (2005) - Exp. 2	Accuracy	1.02	0.2	Yes	0.14	0.2	0.14	0.20
	RT	-0.29	0.2	No				
Russell and Driver (2005) - Exp. 3	Accuracy	0.55	0.22	Yes	0.00	0.22	0.00	0.22
	RT	-0.36	0.22	No				
Russell and Driver (2005) - Exp. 4A	Accuracy	1.14	0.24	Yes	-0.55	0.24	-0.55	0.24
Russell and Driver (2005) - Exp. 4B	Accuracy	1.08	0.24	Yes	-0.05	0.24	-0.05	0.23
Russell and Driver (2005) - Exp. 5	Accuracy	0.42	0.22	No	0.55	0.22	0.55	0.22
	RT	0.28	0.22	No				
Schnuerch et al. (2016) - Exp. 1	RT	0.22	0.13	Yes	-	-	-	-
Schnuerch et al. (2016) - Exp. 2	RT	0.21	0.13	Yes	-	-	-	-
Wood and Simons (2019) - Exp. 1	Accuracy	0.83	0.08	Yes	-	-	-	-

Study	Implicit processing				Awareness assessment			
					Lax		Strict	
	Measure	*z*	SE(*z*)	Sig.	*z*	SE(*z*)	*z*	SE(*z*)
Wood and Simons (2019) - Exp. 2	Accuracy	-2.34	0.07	No	-	-	-	-

Note. Contrasts using different measures of implicit processing within the same experiment (including the same participants) are presented on separate lines; these contrasts were combined with the multilevel meta-analytic model. Awareness effect sizes are available only for experiments that used group assessment of awareness (see "Methods") and are shown for lax and strict criteria when both were reported separately in the paper; otherwise, the same value is used for both criteria. *z* = correlation estimate on Fisher's *z* scale; SE(*z*) = standard error of the effect size estimate; Exp = experiment; RT = reaction time.

The random-effect analysis of the overall implicit effect size showed a mean effect size of .33, with a 95% confidence interval (CI) ranging from .21 to .45. This overall effect was significant (t =5.43, $p < .001$). A heterogeneity test revealed a significant result as assessed by the Q statistic ($Q(85) = 1679.69$, $p < .001$), with a large heterogeneity value of $I^2 = 89.98\%$. The limits of CIs varied widely across experiments, which prompted us to search for outliers. Two approaches were employed to identify outliers. First, outliers were assessed by searching for CIs that fell outside the limits of the pooled effect size with 95% CIs. Second, an influence analysis was conducted using the leave-one-out method (Viechtbauer & Cheung, 2010) to examine if any of the effect sizes exerted a disproportionate influence on the model.

These procedures identified two outliers (Russell & Driver, 2005, experiment 2; Wood & Simons, 2019, experiment 2). Re-fitting the model after excluding the outliers led to a similar overall effect size (.35, 95% CI = [.27; .44]), with similar significance level ($t = 8.33$, $p < .001$). Also, although the heterogeneity value fell to $I^2 = 75.81\%$, the heterogeneity test was still significant ($Q(82) = 293.70$, $p < .001$). Moreover, whereas the variance estimate within studies was not significant (.0248, $p = .36$), there was a significant variation between studies (0.061, $p = .006$), suggesting clustering by moderator variables between studies. We explore this in the moderator analyses reported later.

To investigate the impact of different criteria to classify participants as aware or unaware, we fit separate meta-analytic models using effect sizes obtained using lax and strict criteria. For lax measures, a two-level model showed an overall effect size of .53, with 95% CI limits of .08 and .80. The overall awareness effect was significant ($z = 2.26$, $p = .02$), indicating that participants' awareness of the US was above chance across studies, according to a lax criterion.

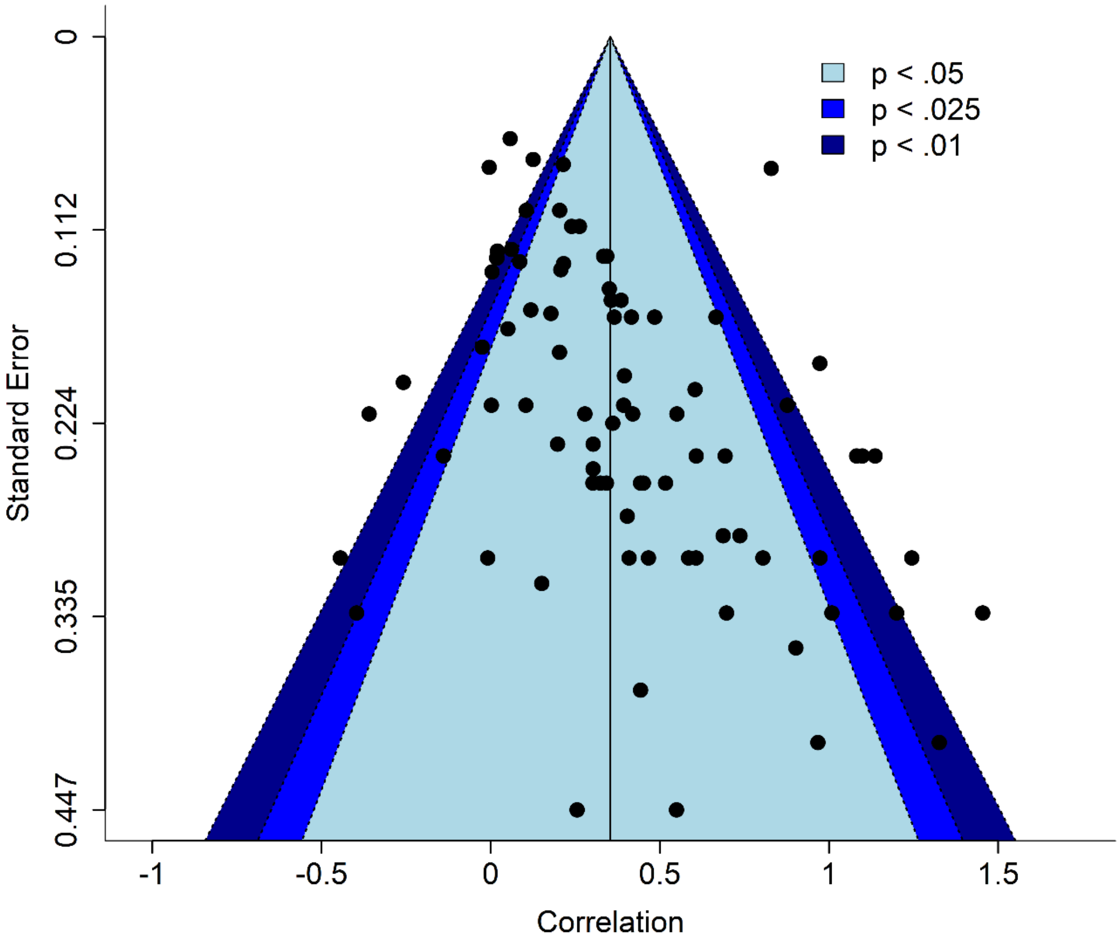
In comparison, when using a strict criterion, the model for effect sizes showed an overall effect size of .40, with 95% CI limits of -.06 and .72. In contrast to the lax measures, awareness was not significantly above chance using the strict criterion ($z = 1.71$, $p = .09$). The mean percentage of aware participants in the lax and strict criteria were 57% and 37%, respectively. Because rates of noticing are expected to vary widely in inattentional blindness experiments, we did not compute heterogeneity statistics for these models. Overall, these results show that the conclusion about whether processing of a US is explicit or implicit depends on the criterion used to categorize participants as aware or unaware.

Publication bias.

To evaluate the presence of publication bias for implicit effects, we visually inspected individual effect sizes on a funnel plot, which shows each effect size against its standard error. In these plots, an asymmetry is indicative of publication bias due to small-study bias (Borenstein et al., 2009). The plot showed an asymmetry (Figure 3-2), which prompted us to investigate if there was a correlation between individual effect size and sample size employing the Begg and Mazumdar's (1994) rank correlation test. A Kendall's tau of 0.328 ($p < .001$) was observed, indicating a risk of publication bias. We further explored the possibility of publication bias using the trim-and-fill method (Duval & Tweedie, 2000). This analysis showed 26 studies missing on the left side (Figure 3-2). After those studies were filled, we fitted the model again to the data, which showed a still significant overall effect ($t(109) = 3.71$, $p < .001$), although the effect size was smaller ($r = .18$, 95% CI = [.08, .28]). Hence, the results suggest that there is a true effect of implicit processing across studies, but there appears to be a bias towards publishing results in the expected direction (i.e., that US are implicitly processed during inattentional blindness).

Figure 3-2

Funnel plot of implicit effect sizes



Importantly, we did not conduct the same publication bias analyses for awareness effects. The reason is that several of the studies reported results for multiple measures, with some of those measures not showing that participants were unaware Thus, we have no reason to suppose that results were selected for publication in a biased manner.

Moderator analyses.

In order to explore whether variations in experimental design influenced implicit effect sizes, we conducted separate analyses for clusters of papers defined by moderator variables. Subgroup analyses were performed in the case of categorical variables, and meta-regressions for continuous variables. We selected variables of interest from our coding procedure presented in Table 3-1, leading to the following list of moderator variables:

1. Relevance of the US (relevant vs. not relevant)
2. Dynamic vs. static
3. Group assessment of awareness (post-hoc data selection vs. group assessment of awareness)
4. Type of implicit measure (RT or accuracy)
5. Number of trials for implicit test
6. Number of participants for implicit test

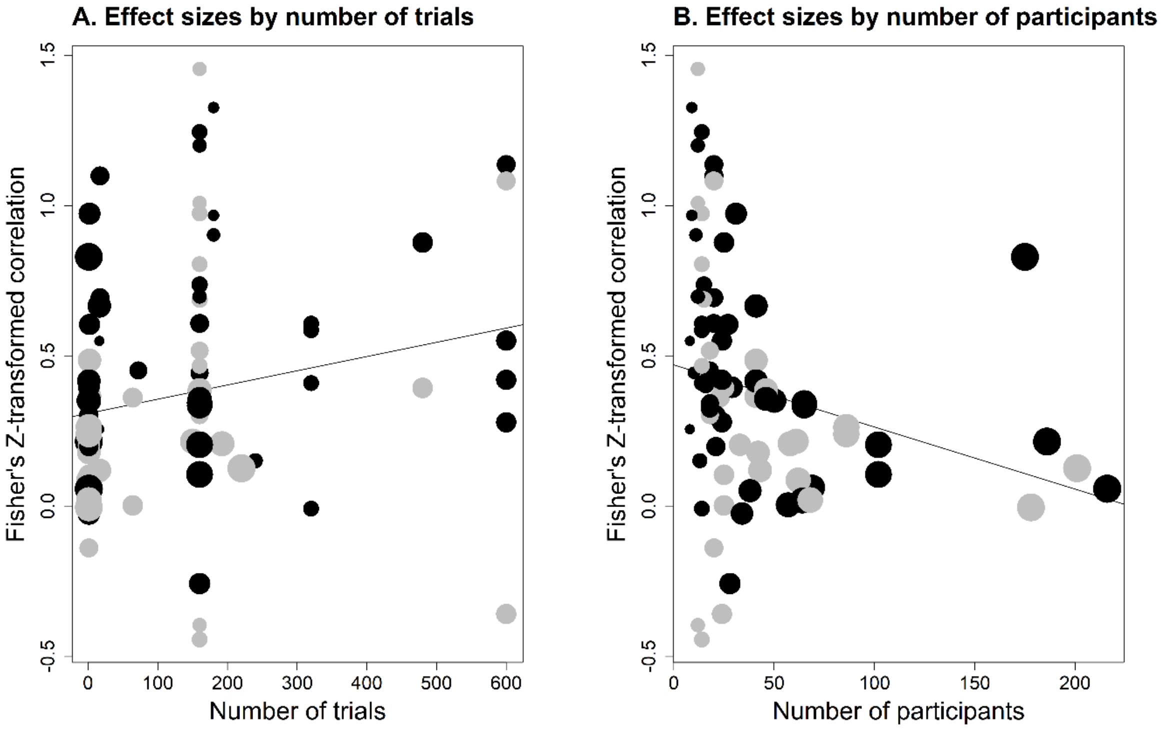
In addition to the moderator analysis using the variables above, we also conducted a subgroup analysis of papers using the inattention paradigm, since they present a uniform design and adopt several methodological precautions not present in the other papers (the inattention paradigm is discussed in detail below). Importantly, those studies often aim to sketch a coherent picture of the relationship between grouping and attention. It is interesting, then, to investigate the general picture of these studies and the impacts of using this particular paradigm through a subgroup analysis.

With regard to US relevance, results showed no significant differences (*t*(81) = 1.53, *p* = .13) in effect size for contrasts with relevant and irrelevant US (*r* = .51, 95% CI [.18, .84] and *r* = .34, 95% CI [.25, .43], respectively). Similarly, no significant differences were observed (*t*(81) = 0.62, *p* = .53) between studies employing a static US (*r* = .37, 95% CI [-.05, .80]) or a dynamic US (*r* = .30, 95% CI [.10, .51]). However, considering group assessment of awareness, a significant difference was observed (*t*(81) = 3.05, *p* = .003) between studies that assessed implicit effects on the whole sample (*r* = .49, 95% CI [.22, .75]) and those employing post-hoc selection of participants (*r* = .24, CI [.14, .35]), with a larger effect for the former. Finally, the implicit effect size for the subgroup of inattention studies was significantly larger (*t*(83) = 2.56, *p* = .01) than in other studies (*r* = .50, 95% CI [0.2436, 0.764] and *r* = .29, 95% CI [0.1931, 0.3859], respectively).

Effect sizes were somewhat different for RT and accuracy (*r* = .32, 95% CI [.07, .59] and *r* = .38, 95% CI [.28, .48], respectively), but this difference was not significant (*t*(83) = -0.63, *p* = .12). Tests for continuous moderators showed moderation both by number of trials (*t*(81) = 2.26, *p* = .03) and number of participants (*t*(81) = -2.28, *p* = .02), indicating that effect sizes increase with number of trials, but decrease with number of participants.

Figure 3-3

Plots of moderation effects for implicit effect sizes by number of trials and number of participants



Note. Black circles represent significant effects; grey circles indicate non-significant effects. Circle sizes are proportional to the precision of the estimated effect.

Discussion

In the current study, we reviewed articles that investigated visual processing of unexpected stimuli (US) outside of the participants' awareness while their attention was directed to an attentionally demanding task. We examined multiple methodological aspects of 39 papers in our qualitative analysis and employed meta-analysis to investigate the occurrence of implicit processing in a set of 59 experiments across a subset of 27 papers. We found evidence for implicit processing of the US across studies. At the same time, our results suggested the presence of publication bias. However, after applying an appropriate method to discard the influence of biased studies, we still obtained significant evidence that the US is implicitly processed, although with a smaller effect size. Overall, our meta-analysis suggests a true effect of implicit processing of the US during inattentional blindness.

The studies reviewed here include experiments performed by Mack and Rock (1998) that possess several features often found in inattentional blindness designs (e.g., the studies reviewed in Kreitz et al., 2020): very few critical trials (in their case, only one); a clear separation between the US and stimuli in the main task; and assessment of awareness immediately after presentation of the US. While the first feature may contribute to unreliable measurements (Vadillo et al., 2016), the last two have been pointed out as important procedures to ensure that the US is actually unattended (Driver et al., 2001; Wolfe, 1999).

One noteworthy feature of the experiments by Mack and Rock (1998) is the use of offline measures to evaluate implicit processing, as opposed to testing for online interference by the US on main task performance. Offline measures have been criticized for being vulnerable to memory issues, since they are only administered after the US has disappeared (Moore, 2001; Moore & Egeth, 1997). Furthermore, they allow for only one measurement of implicit processing per participant, instead of the multiple measurements that can be performed using online measures.

Despite those criticisms to the design of Mack and Rock (1998), similar findings have been reported in studies using online measures. For example, Schnuerch et al. (2016) also found implicit semantic processing during inattentional blindness using online measures administered in multiple trials. Likewise, six experiments (Kreitz et al., 2015a, experiment 2; Kreitz et al., 2016a; Kreitz et al., 2016b; Redlich et al., 2019, experiment 2) reviewed by Kreitz et al. (2020) assessed implicit US processing in a dynamic inattentional blindness task using offline measures. This task was based on Most et al. (2005, experiment 8), that used an online measure (decrement in accuracy in the main task when the US was presented) and found that the US was implicitly processed despite considerable heterogeneity between the stimuli across experiments. Four of the six experiments (Kreitz et al., 2015b; Kreitz et al., 2016a) reported by Kreitz et al. (2020) also found implicit processing of the dynamic US (Table 3-2). Thus, in spite of being vulnerable to a number of issues, offline measures appear to lead to results that match those obtained with online measures.

Wood and Simons (2019) attempted to replicate the results of Mack and Rock (1998) using a large sample (*n* = 216) but did not succeed. This replication's effect size was also a clear outlier in our meta-analytic model. However, this experiment incorporated some modifications into the stimulus selection process compared to Mack and Rock (1998). Specifically, very low-frequency prime words were selected, which might have reduced the priming effect on the stem-completion task, leading to a non-significant result. Moreover, in contrast with Mack and Rock (1998), Wood and Simons (2019) did not conduct control experiments to determine the base rate of choice of the words employed as primes, making it difficult to assess how often they would be chosen in stem-completion tasks without priming.

Moore and Egeth (1997) criticized the use of offline measures, and their work was widely influential on subsequent experiments about implicit processing during inattention: Several studies (Ariga et al., 2007; Lo & Yeh, 2008; Moore et al., 2003; Moore et al., 2004) followed their recommendations regarding the use of online measurements. Moreover, the results of Moore and Egeth (1997) have been successfully replicated in two studies (Lo, 2018; Wood & Simons, 2019, experiment 1). In particular, Wood and Simons (2019, experiment 1) used a large sample (*n* = 165) in their replication of Moore and Egeth (1997). The number of participants whose responses were influenced by the illusion was comparable to that of the original study (*r* = .68, close to the effect size of .70 observed in the original study). This was the case even though Wood and Simons (2019) employed only a single illusion-trial, in contrast to the 16 trials in Moore and Egeth's study.

On the other hand, Moore and Egeth's (1997) study was criticized by other authors (Driver et al., 2001; Lamy et al., 2006) on the grounds that, in their experiment, the proximity between the target lines and background dots might have led to the target falling within the attended area; that is, the background might have received spatial attention, so that the grouping was not truly unattended. Additionally, since both the dots and the lines were presented in the same color, they might have formed a common group based on color, which might have attracted attention. Thus, it is possible that attentional processes have inadvertently influenced the results of Moore and Egeth (1997). A similar observation had already been made by Mack and Rock (Mack et al., 1992; see also Russell & Driver, 2005), who argued that, for stimuli to be really unattended, they should not only be task irrelevant, but also clearly separated from target items.

Supporting this interpretation are the results of Lamy and colleagues (Lamy et al., 2006). They conducted an experiment similar to experiment 3 of Moore and Egeth (1997), using the Müller-Lyer illusion to compare the effect of the illusion during inattention between two conditions: in one condition, the lines were in the same color as the dots; in another condition, they were in a different color. They found that the illusion occurred even in the different-color condition, thus removing the confound pointed out earlier. Importantly, however, the illusion was weaker when the lines were different than when they were in the same color, which may be taken in support of an attentional leak to the US.

Lo and Yeh (2008) performed an experiment similar to Moore and Egeth (1997), but found a smaller effect size. Their design incorporated the modification that, instead of dots, the background matrix was composed of Gabors, which could be oriented horizontally or vertically. Even though they reproduced a bias in line-length judgement, this effect was only detected when the stimuli were presented for 500 ms, and not for the 200 ms condition. Intriguingly, the latter stimulus duration corresponded to the duration used in Moore and Egeth's study. This fact may indicate that texture segregation, which is necessary to extract the lines composing the illusion along the Gabors, demands a longer presentation time to occur without attention. Importantly, the effect size observed for the 500 ms experiment (r = .58) was lower than the effect reported by Moore and Egeth (1997; r = .70).

Other studies conceptually based on Moore and Egeth (1997) include: Moore et al. (2003), which provided results in support of the hypothesis that surface completion occurs without attention, but with a much smaller effect; Ariga et al. (2007), which found a same-object advantage induced by illusory figures when participants were aware of the figures (experiment 1), but not when they were unconscious due to inattentional blindness (experiment 2); and Moore et al. (2004) and experiment 2 in Lo and Yeh (2008), which found no evidence that simple unattended visual shapes elicit a Simon effect. These results suggest that surface completion, same-object advantage and response-end processes, such as the Simon effect, all demand attentional resources. Nonetheless, all of those studies used small sample sizes (below 30), and most of them included only a few trials in which the US was presented. Therefore, it is also possible that those studies were simply underpowered to detect the effects. Indeed, our moderator analysis indicated that the effect size increases with the number of trials. However, this effect was very small and should be interpreted with caution.

It is interesting to compare our results with the previous meta-analysis by Kreitz et al., 2020, which investigated effects of implicit processing of US during inattentional blindness across 16 experiments, 14 of which employed only visual stimuli. They found a small but significant effect (d = 0.153, or r = .076, p < .01) across those 14 experiments. In the current review, we extend those findings and provide evidence that the effect observed by Kreitz et al. (2020) appears to generalize to other inattentional blindness tasks.

The effect sizes observed in our meta-analysis indicate that implicit processing extend to perceptual organization processes, such as surface completion by Kanisza configurations (Moore et al., 2003), in which patterns of stimuli that are organized according to grouping or segmentation rules (Kimchi et al., 2016; Wagemans et al., 2012) change in the background. These are mid-level vision processes that segment input images into objects and background surfaces and precede later processes of visual recognition (Kubilius et al., 2014). Similarly, high-level processing appears to occur for unattended stimuli, such as semantic processing (Mack & Rock, 1998; Schnuerch et al., 2016).

The fact that these mid and high-level processes occur during inattention contrasts with what is observed when stimulus strength is manipulated by paradigms such as continuous flash suppression, in which no such processing is observed (Moors et al., 2016; Moors & Heyman, 2014). Thus, even though both attention and stimulus strength are necessary for awareness of visual stimuli, limiting either has distinct consequences for the type of processing that can occur for unreported stimuli. This is in line with the framework of the neural workspace theory, in which attention and stimulus strength both contribute to consciousness, but influence distinct levels of processing. On the other hand, the few studies (Lo & Yeh, 2008, experiment 2; Moore et al., 2004) that investigated if response interference takes place for unattended stimuli, employing the Simon Effect, found negative results (Table 3-2). This may indicate that processing of stimuli for response selection cannot occur without attention, although this has not been extensively studied in inattentional blindness experiments to date.

Even though the overall effect size found in the present meta-analysis was much higher ($r = .35$) than the effect found by Kreitz et al. (2020), this difference might be partly explained by methodological differences between studies. Particularly, several studies in our review used the same paradigm (the inattention paradigm), which employs a method to categorize participants as aware or unaware that may lead to higher estimates of implicit processing. We discuss this group of studies below.

Inattention Paradigm

In addition to the criticisms on Moore and Egeth’s (1997) design discussed above, Driver et al. (2001) argued that the close proximity of the presented dots might have led to a confound with the observed effects of grouping, such that the effects might actually reflect the blurring of low spatial frequency channels. In an attempt to solve those methodological problems, Driver and colleagues (2001) proposed a different paradigm, which they named the Inattention Paradigm (Driver et al., 2001; Russell & Driver, 2005). This paradigm is not usually referred to as “inattentional blindness”, but it does follow the same general design.

In those inattention studies, participants perform an attentionally demanding detection task using a central matrix composed of black and white pixels. Specifically, the task requires participants to detect small changes over two sequential presentations of the matrix interspersed with a brief blank screen. The blank screen makes the change more difficult to discriminate, in a similar manner to change blindness experiments (Rensink, 2010). Stimuli are presented in the background surrounding the target in one of several configurations, e.g., grouping in rows or columns. The background configurations either change or stay the same after the blank screen.

The rationale for the inattention paradigm can be described as a combination of change blindness and contextual cueing (Driver et al., 2001): changing the background configuration (the visual context) across frames facilitates the detection of a small change in the matrix, compared to identical background configurations. The specific context may consist, for example, in the presence vs. absence of some form of perceptual grouping. Employing this paradigm, a series of studies (e.g., Russell & Driver, 2005) investigated the effect of a number of variables on the interference exerted by the background on the matrix task. Examples of those variables include distance between the background changes and the matrix, matrix/background presentation time, and large saccades intervening between the two matrix presentations.

Our moderator analysis showed that studies employing the inattention paradigm displayed much larger effects of implicit processing than other studies ($r = .50$ vs. $r = .29$, respectively). The reason for this difference is not clear. Overall, inattention paradigms present several advantages when compared to other studies in the review: they employ online measures instead of retrospective measures of implicit processing (when there is an interval between critical trial and awareness assessment; see “Measures of Awareness” section); they include multiple critical trials, which results in larger effect sizes, according to our moderator analysis; and the US is clearly distinct from the stimuli in the main task. One or some of those characteristics may be responsible for the large effect found for those studies. However, it is also possible that this difference in effect sizes is an artifact of how participants are selected in this paradigm: all inattention studies test for implicit effects using the whole sample (group assessment of awareness), including both aware and unaware participants. As we argue below (“Measures of Awareness” section), it is possible that this method of awareness testing leads to inflated rates of implicit processing.

A second issue with inattention studies is that the change in background configuration for some types of grouping might simply not be salient enough to interfere with the main task (Rashal et al., 2017). Concerning this point, Razpurker-Apfeld and Pratt (2008) used the inattention paradigm and ERPs to investigate implicit similarity grouping in columns and rows (simple grouping), or in triangle/arrow shapes (complex grouping). They observed that, despite their behavioral results suggesting that only simple grouping occurs during inattentional blindness, ERP differences between random and grouped stimuli were observed for both types of grouping. Thus, it may be the case that grouping processes differ in detectability according to the nature of measurements, which complicates a comparison between types of grouping based on patterns of significant vs. non-significant results. This issue is especially important because inattention studies propose to distinguish between different types of grouping processes regarding their attentional demands, often finding that some types of grouping occur during inattention whereas others do not (Rashal et al., 2017; Razpurker-Apfeld & Pratt, 2008).

Measures of Awareness

In addition to the meta-analysis of implicit effects, we also used meta-analytic models to examine the impact of different criteria to categorize participants as aware or unaware in studies which tested for awareness in the whole sample instead of testing participants individually. We followed the distinction used by Wood and Simons (2019) between “lax” and “strict” measures, as described in our Methods section. For lax measures, results suggest that participants were aware of the US, which implies that the processing of the US was explicit and not implicit. For strict measures, such processing did not differ from chance. Thus, the conclusions of studies may change depending on the choice of criterion to categorize participants as aware or unaware.

Measures of awareness can be classified as objective and subjective (Seth et al., 2008). Objective measures are based on performance and assume that a stimulus is conscious if the subject performs above chance level in a detection or categorization task, such as forced-choice recognition (Dehaene & Changeux, 2011). In those tasks, responses can be categorized as correct or incorrect (Kingdom & Prins, 2010). On the other hand, subjective measures of awareness rely on subjective reports such as ratings of visibility (e.g., the Perceptual Awareness Scale, or PAS) or higher-order reports such as confidence ratings (Dehaene & Changeux, 2011; Sandberg et al., 2011). In subjective tasks, responses cannot be evaluated as correct or incorrect (Kingdom & Prins, 2010).

The issue of whether objective or subjective measures are preferable to assess awareness is a matter of current debate (Zehetleitner et al., 2015). It has been argued that objective (e.g., forced-choice recognition tests) and subjective (e.g., confidence ratings) measures of awareness differ in sensitivity (Sandberg et al., 2011). Subjective measures have been criticized for being contaminated by changes in response criterion (Schmidt & Vorberg, 2006). On the other hand, objective measures, such as forced-choice tasks, might yield above-chance performance even when participants cannot report stimuli in plain sight (Seth et al., 2008; Mack & Rock, 1998), and thus overestimate consciousness. Others have proposed that tasks like forced-choice recognition benefit from both implicit and explicit processes (Bressan & Pizzighello, 2008; Jacoby, 1991; Roediger III et al., 2007; Seth et al., 2008), and therefore are unable to distinguish between conscious processing and implicit processing (Dehaene & Changeaux, 2011). Furthermore, forced-choice recognition tasks may be performed based on familiarity (Roediger III et al., 2007), which, even if considered under the spectrum of consciousness, is qualitatively different from consciousness as observed in recollection and in conscious perceptual awareness.

Another important issue in assessing awareness concerns the use of retrospective measures, i.e., when there is an interval between the critical trial and the assessment. Delays between stimulus presentation and testing for awareness of that stimulus allow for forgetting, interference, and intrusion of extraneous content (Ericsson & Simon, 1984). In those cases, alternative explanations for negative responses to awareness measures are possible, such as memory issues ("inattentional amnesia", Wolfe, 1999), with participants who were aware of the critical stimulus during its presentation being categorized as unaware. As a result, processes which can only occur when a participant is aware of a stimulus may be erroneously assumed to occur without awareness. In this review, several studies employed long delays after US presentation to assess awareness (see Table 3-1).

Memory issues may not be entirely avoidable in inattentional blindness experiments. Nonetheless, they may be more severe in block designs, when long blocks replace the single critical trial of more typical inattentional blindness designs (e.g., Mack & Rock, 1998). Long blocks of inattention trials may increase statistical power for tests of implicit US processing, avoiding the need for large samples when designs such as those of the classical studies by Mack and Rock (1998) are employed (Gabay et al., 2012). It also allows for the use of measures that might detect effects not accessible to behavioral measures, but which demand large numbers of trials, such as ERPs (Pitts et al., 2012; Razpuerker-Apfeld & Pratt, 2008).

However, block designs have the disadvantage of not allowing to determine the point of the experiment when participants become aware of the US, since awareness is only probed once and at the end of the block. This may result in grouping together aware and unaware trials, which might lead to an explicit effect being erroneously interpreted as implicit. Additionally, using long blocks may also increase the chance that participants briefly perceive the US but forget about it when probed (Mack & Rock, 1998). Thus, although immediate testing after the first appearance of the US results in a limit of one critical trial by participant, this design might be preferable to avoid mixing of implicit and explicit results.

Testing time may be more or less critical depending on what aspects of the stimulus participants are questioned about. Specific details about visual stimuli may be less successfully encoded and more prone to forgetting than gist memory (Ahmad et al., 2017; Rocha et al., 2013). This is important for studies on implicit processing during inattentional blindness, since the features about which participants are asked about varied considerably across studies. For example, memory of the US may be worse for detailed information (e.g., “what were the patterns in the background?”) than for coarse information (e.g., “were there patterns in the background?”).

Thus, asking participants to describe the US in detail may not detect awareness of high-level, abstract properties of the stimuli, also known as ensemble representations (Whitney & Yamanashi Leib, 2018). Recently, Ward et al. (2016) showed that, when appropriate questions are posed, individuals can report statistical ensemble properties of color diversity for visual stimuli but are unable to report individual colors. Similar observations have been reported for size discrimination, face recognition and other visual features (see Whitney & Yamanashi Leib, 2018).

Thus, asking participants for details about the US may not detect awareness of high-level properties, which in some cases might suffice to exert an effect on measures of implicit processing, e.g., interference of background configuration on performance in a central task. This is the case even if explicit ensemble representations do not demand (explicit or implicit) representation of individual features (Ward et al., 2016). The numerous observations of ensemble representations formed in the absence of attention (e.g., Corbett & Oriet, 2011; Peng et al., 2019; Whitney & Yamanashi Leib, 2018) provide empirical support to this suggestion.

Along these lines, some studies (Razpurker-Apfeld & Pratt, 2008; Russell & Driver, 2005) reported that participants responded affirmatively to questions about whether they perceived something in the background, even if they could not report what it was. However, participants were still treated as unaware of the stimuli if they could not identify the US in a forced-choice task, for example. In other studies, participants were considered aware only if, in addition to reporting noticing a pattern, they could also describe it. Studies with such requirements often found low rates of noticing. For example, Schnuerch et al. (2016, experiments 1 and 2) reported noticing rates of 6 and 8 percent, which were 1.65 and 1.72 standard deviations below the mean noticing rate of 50.7 percent.

To investigate the impact of such variations, Wood and Simons (2019) employed two distinct criteria to group participants on the basis of awareness: a lax criterion, according to which they had to report noticing a pattern even if they could not recall that pattern; and a strict criterion, according to which they also needed to select the correct pattern in a forced-choice task. The proportion of participants who were aware of the patterns by the lax criterion was much higher than by the strict criterion (32% vs, 16.5% in experiment 1; 51.8% vs. 31.3% in experiment 2).

The studies described above suggest that forced-choice measures may lead to very different conclusions about awareness than simple recall questions. In the case of Razpurker-Apfeld and Pratt’s (2008) study, for example, all participants detected something else in the background, while forced-choice discrimination was low (1 participant out of 14). Other studies (Moore & Egeth, 1997; Moore et al., 2003; Moore et al., 2004; Lo & Yeh, 2008; Rashal et al., 2017) also assessed awareness with multiple questions. However, those studies did not analyze the impact of each measure in their results. Instead, when significance tests showed that the proportion of noticers did not deviate from chance according to at least one of the measures, the analysis of implicit processing was carried out assuming lack of awareness or attention.

Although measuring awareness is notoriously difficult, using more demanding measures to classify participants as aware or unaware may lead to incorrect classifications. On the other hand, measures with very low demands, such as asking “Have you noticed anything else in the background?”, might be susceptible to effects of experimenter effects (Rosenthal, 1966) if participants feel they are supposed to respond affirmatively. They may also result in high rates of false positives due to false alarms, leading to large numbers of exclusions and increasing the number of participants necessary to achieve a sufficient sample size for analysis.

Fortunately, this may not be an issue for all designs. Wood and Simons compared implicit effects for unaware participants selected according to their lax and strict criteria and observed that the proportions of participants responding according to the illusion was comparable across conditions (84.2% vs. 80.7% in experiment 1 for lax and strict criteria, respectively; 0.9% vs. 1.0% in experiment 2). When a distinct procedure is used to assess awareness, however, the sensitivity of awareness measures may be a more serious issue. Specifically, some experiments performed what we called “group assessment of awareness”: instead of selecting participants by individual awareness results, they tested if the sample as a whole noticed the US more often than chance. When they did not, the whole sample (including both aware and unaware participants) was analyzed for processing of the US. If the analysis showed that the US was processed, the study concluded that the US was implicitly processed during inattention. The issue with this procedure is that it is possible that processing of the US occurs only for aware participants, and that, if analyzed separately, aware and unaware participants might exhibit distinct results for the processing of the US. On the other hand, when both aware and unaware participants are pooled together and considered unaware as a group, testing for implicit processing in the group might yield significant results due to the aware participants only. In this case, the study would arrive at the incorrect conclusion that there is implicit processing of the US for unaware participants when there is none.

It may also occur that the same process might occur for both aware and unaware participants, but the magnitude of its effect on responses to the task might be larger in the first group than in the second. In this case, pooling aware and unaware participants might inflate the results for implicit processing, leading to overestimates of effect sizes. Our moderator analysis of group assessment of awareness on implicit processing suggests that this might be the case: studies that employed this method resulted in larger effect sizes than studies that employ post-hoc selection of participants ($r = .48$ vs. $r = .24$, respectively). This issue does not occur for experiments that select participants for analysis according to their individual performance on awareness tests ("post-hoc data selection"; e.g., Mack & Rock, 1998; Schnuerch et al., 2016). This method has its own problems, however, discussed in the next section.

Regression to the Mean and Implicit Processing

Several papers in this review are affected by regression to the mean, as a consequence of using post-hoc data selection to investigate unconscious processing (Shanks, 2017). This occurs when experimenters select a subgroup from the study sample according to some baseline score or the result of a post-hoc statistical test for awareness of a stimulus. The performance of participants in this subgroup is then tested in a task that demands processing of that stimulus. A level of performance above chance is taken as evidence of processing without awareness. The issue of regression to the mean arises because awareness is imperfectly correlated with measures of performance.

Cohen et al. (2003) explains how regression to the mean necessarily occurs when two variables exhibit a correlation below 1.0 and extreme values of one variable are selected. In the case of post-hoc data selection for awareness, when subgroups from one extreme of the sample scores on the awareness test are selected, the scores on the performance measures (implicit processing measures) will regress toward the mean. If the mean of performance scores of the whole sample is above 0, then the subgroup's average performance will regress toward that level, possibly resulting in false positives for implicit processing.

Another issue with this procedure is related to the statistical power of awareness tests. Studies on implicit processing typically assess awareness with measures such as recognition or recall tests and evaluate deviations from chance with null hypothesis significance tests (NHST). Participants are usually considered unaware when null results are thereby obtained. However, the outcome of these tests depends on their statistical power, which in turn depends on the number of trials for the assessment (Vadillo et al., 2016). Crucially, as seen in Table 3-1, most awareness assessments in the studies in this review had only one trial. If statistical power is low due to a small number of trials, the tests might not detect a significant deviation from chance even if participants are actually aware of the US. In contrast, the number of trials to assess implicit processing varied from one to 600.

Additionally, as previously discussed, while the awareness assessments were always retrospective, most of the implicit measurements were performed online, hence likely providing higher sensitivity than the offline awareness measures (Lovibond & Shanks, 2002). In that case, a statistical test for implicit processing will have higher power than an awareness test. This combination of high-powered implicit tests and low-powered awareness tests may lead to a null result for awareness, even if some participants are aware, and to a significant result for implicit processing, even if only aware participants process the US. In that case, the study would arrive at a false conclusion that there is implicit processing of the US.

Given the above issues, it may be preferable to avoid group assessment of awareness and post-hoc data selection altogether. Shanks (2017) lists three alternatives to post-hoc data selection. The first consists in using two different measures of awareness, one to select unaware participants and the other to estimate awareness in that subsample. The example suggested by Shanks (2017) of selecting odd and single trials is not possible in IB experiments like the ones reviewed here, where participants are typically assessed for awareness only once (or once for each measure, when multiple measures are used). A second option is to compare the performance of unaware participants against the performance predicted by regression to the mean alone or correcting for regression to the mean. Lastly, Shanks (2017) suggests that researchers avoid post-hoc data selection completely, and instead select unaware participants using experimental manipulations instead of measured variables. However, even though this is a possibility in investigations employing methods such as CFS and masking (Breitmeyer, 2015), attention is usually not amenable to reliable manipulation, so this suggestion is probably not an alternative for studies on inattention.

Finally, studies on implicit processing in inattentional blindness might benefit from extending Lovibond and Shanks' (2002) recommendations for assessment of the relationship between conditioning and awareness to the investigation of implicit processing during inattentional blindness and awareness. These recommendations are: a) a null outcome in a test of US processing between aware and unaware participants; and b) a significant outcome in a test between conditions of US processing (US present vs absent) unaware participants alone.

Final Considerations

The issue of whether stimuli that are processed under inattentional blindness are indeed unattended and unconscious is an intricate question. It has been suggested, for example, that an unexpected stimulus, which would trigger an attentional shift in regular conditions, may unconsciously capture a small amount of attention even if subjects are inattentionally blind (Bressan & Pizzighello, 2008; Rashal et al., 2017). The investigation of this relationship is constrained by the limitations of the current state of knowledge on attention, which comprises several subtypes that are not clearly distinguished and cannot be measured unambiguously. Moreover, a lack of consensus on how to appropriately measure awareness opens the conclusions often made about unconscious processing to methodological criticism.

Overall, the current meta-analytic results for implicit processing during inattentional blindness indicate a real effect, despite the variability in the studies reviewed here. However, the conclusions for awareness are less straightforward. Although measuring awareness is far from simple (Sandberg et al., 2010; Zehetleitner & Rausch, 2013), we believe that the current review contributes to highlight the importance of employing adequate methods to assess awareness when designing studies on implicit processing during inattentional blindness.

Lastly, we would like to consider the possible implications of our discussion to a particular theoretical distinction that has been vigorously debated in recent years. This distinction proposes two types of consciousness: phenomenal consciousness vs. access consciousness (Block, 2007; Lamme, 2003, 2004). Phenomenal consciousness refers to the subjective experience of perception, for example, seeing, whereas access consciousness consists of cognitive contents that are selected by attention for further processing, for example, reporting or decision-making. Since measures of awareness require participants to report a stimulus, they are believed to measure only access consciousness (Block, 2007). Hence, it is possible that inattentionally blind participants experience the US (i.e., are phenomenally conscious of the US), but the stimulus fails to be selected for further processing. Despite its plausibility, it is nevertheless difficult to conceive how this sort of consciousness might be measured.

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CHAPTER 4. IMPLICIT TEXTURE SEGREGATION DURING INATTENTIONAL BLINDNESS

Published as a data article:

Nobre, A. P., Nikolaev, A. R., & Wagemans, J. (2020). High-density scalp EEG data acquired in an inattentional blindness paradigm with background Gestalt stimuli. Data in Brief, 28, 104901. https://doi.org/10.1016/j.dib.2019.104901

Abstract

A recent experiment revealed event-related potential (ERP) correlates of inattentional blindness using a texture segregation task (Pitts, Martínez, & Hillyard, 2011). In this study, we aimed to replicate that experiment. Thirty-seven participants performed an attentionally demanding task while on the background multiple white lines changed orientation on each trial. In 40% of trials, the lines formed a square pattern; on other trials the orientations of the lines were random. The experiment comprised one practice session and three test sessions. After the first and second sessions, an awareness questionnaire was administered to the subjects to assess if they noticed the square. Based on the participants' responses, they were categorized as aware or unaware of the square. EEG was recorded from 256 electrodes during all sessions. Mean ERP amplitudes were extracted from two time windows (220-280 and 300-340 ms after stimulus onset, where the original study showed ERP effects of texture segregation and awareness, respectively) over the parietal-occipital regions. A difference in the first time window was observed between square and random patterns in sessions 2 and three. However, contrary to the findings of the original study, no differences between the patterns were observed in session 1 for either group. The same pattern of results was observed for the second time window. No effects of group were found in either window. Correlation tests showed no correlation between mean amplitudes in the second time window and questionnaire responses. Thus, we only partially replicated the results by Pitts et al. (2011). We discuss the implications of those results for the relationship between attention and implicit texture segregation and for inattentional blindness paradigms.

Keywords: attention; electroencephalography; Gestalt; texture segregation; awareness

The study of unconscious processes has gained considerable attention in the last decades within cognitive science. Not only is the topic theoretically relevant, for example, for theories of consciousness (e.g., Dehaene & Charles, 2014; Pitts et al., 2018), it has also been used to characterize neuropsychological disorders (Weiskrantz, 1990). Furthermore, implicit biases and associations have been the target of several studies (De Houwer et al., 2009; Greenwald et al., 2015), with unconscious bias training being employed in several organizations nowadays (Noon, 2018).

Nevertheless, the relationship between awareness and multiple cognitive processes is not well understood. In visual processing, one of the functions commonly attributed to consciousness is information integration: the combination of independent features, such as color, location and motion, into a unified percept (Mudrik et al., 2014). Specifically, it has been suggested that integration might be one of the hallmarks which differentiate conscious processing from unconscious processing: whereas unconscious processing of visual input is carried out separately in parallel, conscious awareness are integrated into a coherent whole.

Several types of integration exist; for example, filling-in phenomena such as the perception of Kanisza shapes (Kanizsa, 1979); and contextual effects of surroundings on the perception of color of a target (Lamme, 2015). There is evidence for some types of integration in the absence of awareness, such as integration between objects and backgrounds into scenes, and between orientation and location (Keizer et al., 2015; Mudrik et al., 2011), while others, such as organization of Kanisza surfaces and perception of faces types, have not been observed outside of awareness (Lamme, 2015; Moors et al., 2016; Shafto & Pitts, 2015). Here, we consider subjects as aware of a stimulus if they are able to report the presence of the stimulus (Merikle, 1984; Seth et al., 2008) Gestalt integration phenomena, such as grouping according to Gestalt laws and figure-ground segregation, have been proposed as a possible boundary between conscious and unconscious processing (Lamme, 2015).

A number of methods are employed to make stimuli unaware to participants. Breitmeyer (2015) lists 24 methods, including manipulations of “stimulus strength” or bottom-up activation, use of bistable figures, and manipulations of attention. Those procedures influence visual processing at distinct levels; for example, some procedures leave semantic processing intact, while others do not (Breitmeyer, 2015). Manipulations of stimulus strength employ procedures such as short presentation times, low contrast and masking (Breitmeyer, 2015; Dehaene et al., 2006) that make stimuli more difficult or impossible to detect or discriminate. Experimental paradigms along this line include binocular rivalry and continuous flash suppression (CFS; Faivre & Koch, 2014). Binocular rivalry consists in the presentation of different images to distinct eyes, leading to perceptual alternations between images, despite both of them being presented continuously (Platonov & Goossens, 2014). This method is believed to activate low-level rivalry mechanisms as early as the LGN or V1 (Breitmeyer, 2015). CFS, by flashing stimuli to one eye, renders stimuli in the other eye unconscious (Tsuchiya & Koch, 2005); the mechanisms involved in this suppression include a reduction in the flow of information to higher visual areas (Moors et al., 2016).

Another method to make participants unaware of stimuli is to manipulate top-down attention. Most theories of attention assume that attention and awareness are somehow related, although the specific nature of this relationship is not clear. Some researchers propose that attention and awareness are dissociable (Koch & Tsuchiya, 2007; Van Boxtel et al., 2010), whereas others consider that attention is necessary for awareness (Dehaene et al., 2006, 2014; Pitts et al., 2018). In this respect, it is not clear how manipulations of attention influence distinct levels of processing, compared to other manipulations. For example, crowding – the impairment in peripheral recognition of cluttered objects (Whitney & Levi, 2011) – and metacontrast masking – backward masking by spatially adjacent stimuli (Breitmeyer & Ogmen, 2006) – both reduce awareness of stimuli, but work by influencing stimulus strength rather than attention. Those manipulations influence distinct levels of the visual processing hierarchy (Breitmeyer, 2015). Hence, when manipulations of stimulus strength provide evidence for implicit integration, such evidence does not necessarily generalize to studies manipulating attention.

In order to investigate the relationship between attention and awareness, some paradigms have been employed to generate situations of inattention while manipulating stimulus features to examine if the stimulus is processed, and, if so, to what extent. Examples include change blindness, attentional blink and dual task designs (Cohen et al., 2012). Another paradigm is inattentional blindness (occasionally referred to as just “inattention”; Most et al., 2005; Pitts et al., 2011; Simons & Chabris, 1999).

Inattentional blindness refers to the absence of conscious perception of an unexpected stimulus when attention is diverted away from that stimulus towards an attentionally demanding concomitant task (Mack & Rock, 2000; Most, 2010). In a typical inattentional blindness experiment, participants are requested to perform an attentionally demanding main task (Most, 2010). At some point during that task (the "critical trial" or "inattention trial"), an unexpected critical stimulus is presented concomitant to the main task, often in the background. Importantly, participants are not informed about this stimulus during the instructions. After the presentation of the unexpected stimulus, participants are inquired about it, and then are requested to continue performing the task, until the same critical stimulus is presented for a second time ("divided-attention trial"). After being questioned once again about the critical stimulus, participants are requested to start ignoring the main task and attend to the critical stimulus instead ("full attention trial"). Typically, some proportion of participants do not notice the critical stimulus during the inattention trial. The number of participants who miss the critical stimulus varies with characteristics of the task such as perceptual load, spatial relationship between main stimuli and the unexpected stimulus, and similarity between the main stimuli and the unexpected stimulus (Most, 2010).

The extent to which the unexpected stimulus is processed during inattentional blindness is a matter of debate. A number of studies have been conducted investigating whether various types of processing occur during inattentional blindness: Simon effect (Lo & Yeh, 2008; Moore et al., 2004), amodal completion (Moore et al., 2003), and modal completion (Moore & Egeth, 1997). Some studies have shown that Gestalt integration processes can occur when participants are unaware of the stimuli due to inattention (Moore et al., 2003), while others found opposite results (Lo & Yeh, 2008; Moore et al., 2004).

It has been suggested that attention is needed for integration of independent visual features into a representation of an object (Allport, 2011; Paul & Schyns, 2003; Treisman & Gelade, 1980). Crucially, the literature suggests that distinct types of Gestalt grouping place different degrees of attentional demands, and therefore lead to different results concerning Gestalt integration during inattention. For example, Kimchi and Razpurker-Apfeld (2004) investigated grouping by similarity during inattention. Participants performed a change detection task on a matrix presented at the center of the screen with two types of trials: same-trials and change-trials. In the background, stimuli could be grouped by similarity, in patterns of columns or rows; or they could be presented with no grouping at all. Implicit grouping was assessed with an online measure, consisting in the interference of changes in the background grouping on the performance in the main task. Results showed better performance in same-trials when the grouping in the background did not change; inversely, performance in change-trials was higher when the background grouping changed as well. This is taken as evidence that participants grouped the elements in the background, which interfered with their responses. Inattention was assessed with a surprise retrospective question about the configurations, the responses to which showed that most participants were unable to report when the configuration of those stimuli changed. Since grouping seemed to occur in the background, as indexed by the online measure, and participants were not aware that such grouping occurred, the authors concluded that grouping had been occurred unconsciously or implicitly. Other studies using the same online measure, but different types of grouping, led to heterogeneous results (Rashal et al., 2017; Russell & Driver, 2005), suggesting that multiple types of grouping are influenced differently by attention (Kimchi, 2009). The reasons for these differences are currently not clear.

One potential issue in the discussion about distinct types of grouping is the nature of the measure of processing employed. Although online measures avoid potential memory issues (Kimchi & Razpurker-Apfeld, 2004; Moore & Egeth, 1997), assessing grouping through attentional costs in a central task assume that such grouping process would compete for brain resources. However, it is possible, and indeed likely, according to resource-directed theories of attention (Pashler, 1998), that unattended processes do not consume resources. A better measure of attention would be an online index of attention that is unrelated to the main task performed by the subject. Event-related potentials (ERPs) constitute such a measure.

To date, only a few studies have investigated EEG correlates of the processing of unconscious stimuli during inattentional blindness (Koivisto & Revonsuo, 2010). One of the reasons for the scarcity of EEG studies in inattentional blindness is the structure of this paradigm. Because participants become aware of the unexpected stimulus after the first inquiry, most inattentional blindness studies have only a single inattention trial. This makes it impossible to investigate the processing of the unexpected stimulus with techniques that require averaging across multiple trials, like ERP.

Pitts and colleagues (2011) investigated implicit texture segregation during inattentional blindness using ERPs. They modified the typical inattentional blindness paradigm to include a large number of trials for inattention, divided attention and full attention conditions. The main task was a contrast detection task, while, in the background, a matrix of randomly-oriented white segments was presented concurrently. Occasionally, the white segments configured into a square within the matrix (the critical stimulus). The authors reported two main results: (1) a negative difference in the ERP amplitude in the time window from 220 to 260 ms (Nd1) between square and random configurations; and (2) a negative difference in the window from 300 to 340 ms (Nd2) between aware and unaware phases. The first negativity suggested that contour integration/texture segmentation could be performed without awareness. The second negativity was interpreted to correspond to the visual awareness negativity (VAN) observed previously by Koivisto and Revonsuo (2010). The authors concluded that texture segregation did not demand attention to occur, and that awareness of irrelevant stimuli could be indexed by the VAN, as proposed by other studies.

Some earlier studies had shown results along the same lines. Yeshurun and Carrasco (2000) observed that attention modulated early responses associated with texture segmentation, consistent with modulation of activity as early as V1. Scholte et al. (2006) used an inattentional blindness paradigm with MEG and fMRI measures to investigate the processing of background checkerboard textures during an RSVP task. They observed higher activity for the textures than for homogeneous backgrounds in inattentionally blind participants. However, they found no difference in early MEG activity (up until 240 ms) related to the unexpected stimulus between aware and unaware participants. The fMRI data showed a similar pattern of results, with differential activity between aware and unaware participants appearing only in V3a. This suggests that attention did not have an effect, in contrast with the results of Yeshurun and Carrasco (2000).

However, not all types of integration are observed without awareness. Even within the domain of Gestalt processes, there is variation among behavioral results with the inattention paradigm (e.g., Kimchi & Razpurker-Apfeld, 2004; Rashal et al., 2017; Russell & Driver, 2005). This paradigm could be employed to investigate further types of integration, such as figure-ground segmentation or motion integration.

With regards to the study by Pitts et al. (2011), there are some caveats which need to be pointed out. First, some behavioral results show contrasting results to the ones shown by Pitts et al. (2011), with no implicit texture segregation being observed during inattention. Additionally, because awareness was assessed only at the end of the blocks, each of which consisted of many trials, it is possible that conscious and unconscious trials were mixed within phases. If that is the case, it is possible that the implicit texture segregation effects observed were actually due to trials where participants consciously perceived the stimuli. In that case, even if texture segregation cannot occur implicitly, the results may point to this due to mixing between conscious and unconscious trials.

Evidence that results concerning implicit processing might actually be caused by conscious or explicit processing comes from a recent meta-analysis (Vadillo et al., 2016). This meta-analytic review pooled several studies which had found implicit learning, and the results indicated that participants in those studies were in fact aware of the stimulus. Moreover, a recent study reanalyzed data from some studies on implicit processing (Shanks, 2017), and found they were unable to reproduce the results. This suggests that it might be important to replicate previous studies which obtained evidence for implicit processing.

The goal of this paper was to replicate the results of Pitts et al. (2011), while introducing some modifications to avoid some potential sources of noise in the results. First, we introduced a procedure to keep task difficulty constant across the task, to try to avoid practice effects. The reason for this change was that, when difficulty is constant across blocks, participants may automatize performance of the task, such that attention might “spill over” to the background. Second, we changed the shape of the background, to avoid having it coincide with the shape of the unexpected configuration. Third, we changed the duration of the unexpected stimulus to avoid confounds between stimulus offset and one of the ERP effects observed in Pitts et al. (2011).

Using the same data as Pitts et al. (2011), a subsequent study (Pitts et al., 2014) analyzed the P3 wave between 350 ms and 550 ms. The rationale for this was that, after the first awareness assessment, background stimuli are conscious, but not task-relevant. In contrast, in the last phase of the experiment, the task was to detect background stimuli; hence, background stimuli were both conscious and task-relevant. They observed a difference in P3 mean amplitude between square and random configurations only in the third phase. Thus, they observed that while the Nd2 reflected awareness of stimuli regardless of task relevance, the P3 indexed the processing of stimuli that were both conscious and task-relevant. In this study, we performed the same analysis on the P3 as Pitts et al. (Pitts et al., 2014).

Additionally, we investigated if pre-stimulus alpha activity influenced implicit processing of the unexpected stimuli and noticing of the unexpected stimuli. Pre-stimulus alpha activity has been observed to influence processing of background irrelevant stimuli and visual awareness of stimuli (Mathewson et al., 2009), as well as the detection of threshold-level stimuli (Ergenoglu et al., 2004). Analysis of alpha activity allows to correlate pre-stimulus alpha activity with ERPs on single trials. We took advantage of this to investigate if pre-stimulus alpha activity at the trial level would predict differences in the Nd2 component reported in the Pitts et al. (2011) paper. We reasoned that, if pre-stimulus alpha activity influenced awareness, we would observe an effect of configuration as a function of pre-stimulus alpha power.

Methods

Participants

Thirty-seven undergraduate Psychology students, participated in the study for credits. Data from two participants were excluded due to problems during EEG recording. Four other participants were excluded because of EEG artifacts revealed during the analysis. One subject was excluded because she did not understand the awareness questionnaire. The final sample consisted of 30 participants (6 male), aged 18-28 years (mean = 20.1, SD = 2.09).

Stimuli

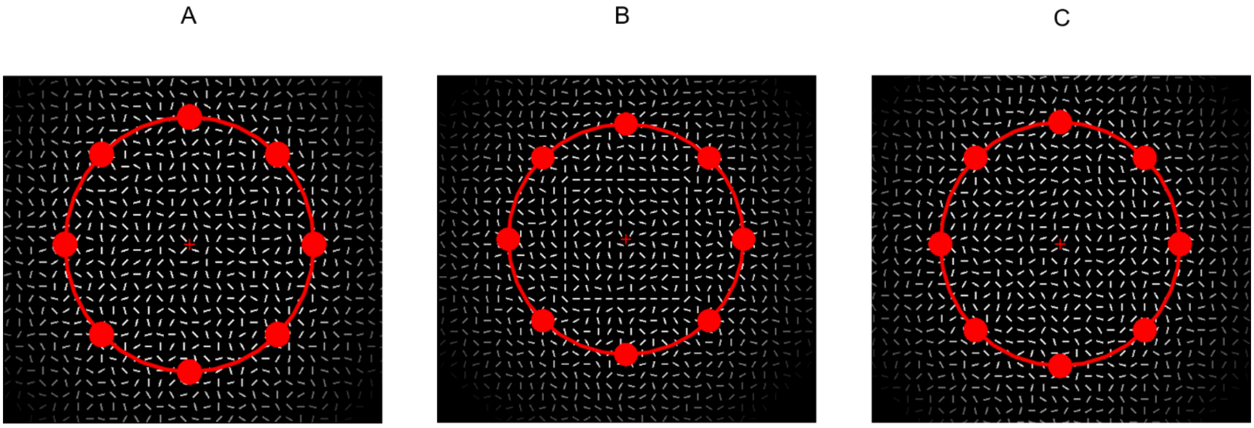
We employed stimuli similar to the ones used by Pitts et al. (2011), with some changes. A red ring (4.9° radius, 13.4 cd/m2) appeared on a dark (0.07 cd/m2) background. Eight discs (1° radius each), matching the ring in color and luminance, were superimposed on the ring. The angular distance between any two neighboring discs was π/4 radians. At all times, a central fixation cross (0.5°), in the same color and luminance as the discs, was present at the center of the screen. During 10% of trials, one of the discs’ luminance was decreased. In the original design by Pitts et al. (2011), a rotation of the ring clockwise or counterclockwise constituted an attention-capturing event intended to prevent participants’ attention from being captured by the changes in the background. To maintain this trial-by-trial attention capturing event, we introduced that another event that coincided with the trial period, consisting of the ring and discs appearing and disappearing in each trial (as described next). With this change, we hoped to avoid subjects from tracking the motion of the ring with eye movements.

In the original study by Pitts et al. (2011), white segments were presented at all times in a background grid, configuring a 20 x 20 square matrix. We decided not to have a background configuration of the same shape as the critical stimulus to avoid any context effects that might lead participants to notice the square. Thus, we increased the size of the grid to 70 x 90 segments, which filled a larger region of the background than the original matrix. The grid was composed of 6300 white segments (0.34° length, 52.5 cd/m2), separated by a distance of 0.46° both vertically and horizontally. A circular inverted Gaussian mask with a radius of 5.65° was superposed on the matrix, so that only a circular region in the center was visible.

The background segments were presented in three different configurations during trials: random, square and diamond (Figure 4-1). In the random configuration, the segments were drawn randomly. In the square and diamond configuration, a subset of the segments was presented randomly to configure a square pattern (3.5° x 3.5°) or a diamond pattern (3.2° x 3.2°), respectively, centered on the fixation cross. During the baseline period, the background was always presented in a random configuration. Trials were separated by a baseline period lasting from 500-700 ms, during which only the fixation cross and the background stimuli were present.

Figure 4-1

Configurations of the background stimuli. A: random configuration; B: square contour; C: diamond contour



Procedure

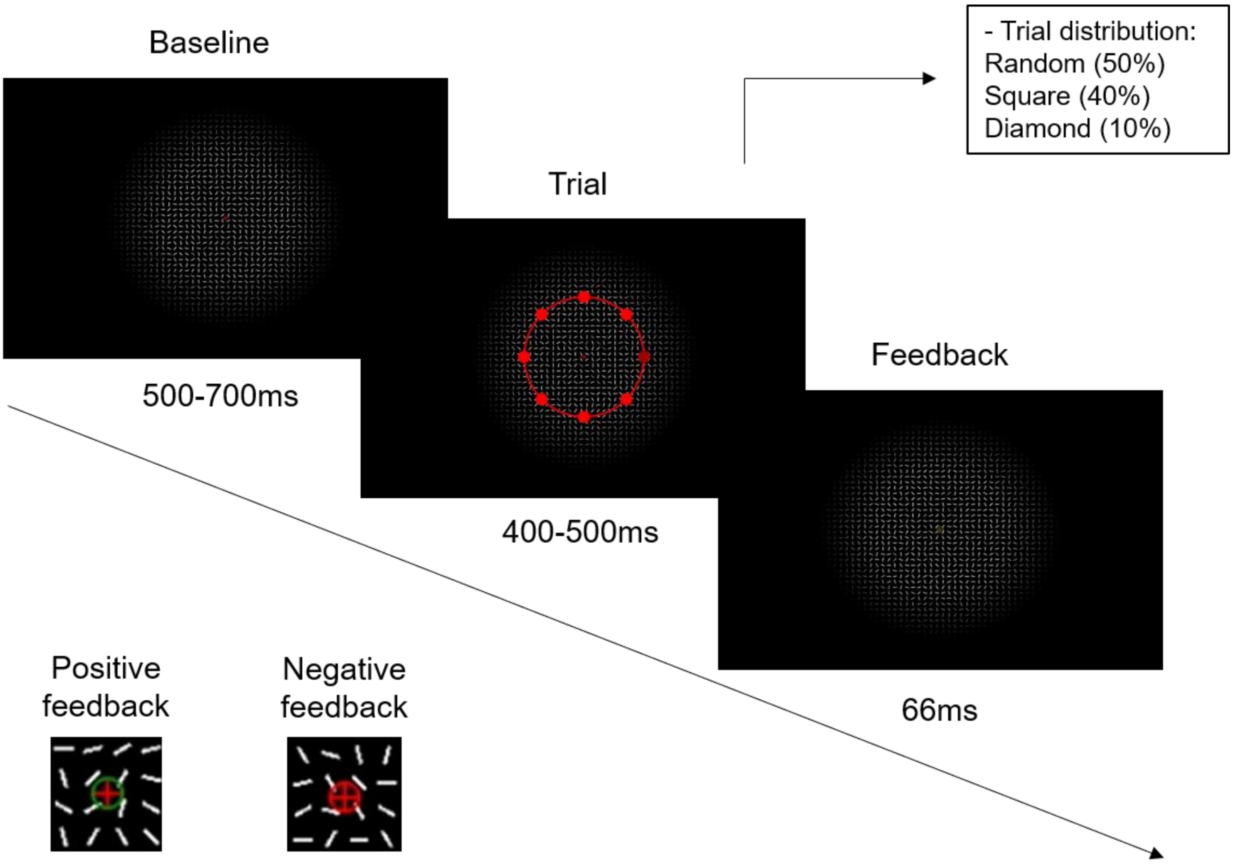
The experiment was conducted in an electrically shielded dark room. Participants sat 57 cm from a 14-inches LED screen with a 60 Hz refresh rate. The task was run using the Psychopy software (Peirce, 2007, 2009). Before the experiment, participants were shown a screenshot of the ring and discs superposed on the white segments, which were configured randomly. The participants' task was to press a space bar with their index finger as fast and accurately as they could when they noticed a darker disc. No mention was made to the participants of the white segments. Participants who inquired about the purpose of the segments were told that they created visual noise in order to make the task harder, but no further comments were made about the segments.

The trial structure is depicted in Figure 4-2. Each trial started with a baseline in which the background segments were presented randomly and neither the disc nor the rings were present. Once every second, remaining on-screen for a period between 400-500 ms. In the study by Pitts et al. (2011), trials had a fixed duration of 300 ms. Because this duration coincided with the onset time of the effects of the Nd2 observed by Pitts et al. (2011), we presented the stimulus for a longer duration and introduced a jitter of 100 ms in the stimulus duration to avoid confounds with the offset of the stimulus.

In each trial, one of the eight discs, determined randomly, had its contrast decreased. In the original study by Pitts et al. (2011), the amount of decrement was fixed in each block. Such a design might allow for practice effects, such that the task becomes easier throughout a session. This might result in the main task being less attentionally demanding in later trials within blocks than in earlier trials. To keep task difficulty constant during the testing phase, we employed a QUEST procedure (Watson & Pelli, 1983) to determine target luminance in each target-present trial, instead of using a fixed decrement. The QUEST is an adaptive procedure which employs prior information to efficiently fit a Weibull psychometric function to the data in each trial; this psychometric function is then used to determine stimulus intensity. The procedure ended when a maximum number of 60 target-present trials was reached.

Figure 4-2

Structure of one trial and examples of positive and negative feedback in the main task following correct and incorrect responses, respectively



Due to the high difficulty of the main task, in contrast to Pitts et al. (2011), we introduced feedback to encourage participants to focus on the main task. A green (for correct responses) or red (for misses or false alarms) circumference with a diameter of 0.22° was presented around the fixation cross immediately after a response, or for 66 ms after the trial period in target-present trials when no responses were emitted.

The experiment was divided in four sessions: one practice session and three test sessions. The practice session comprised five blocks of 60 trials each, while the test phases had 10 blocks of 60 trials each. Between blocks, participants had self-paced pauses. They started the next block by pressing the space bar. During practice, no patterns were presented among the segments. Participants were not informed that the first session was actually a practice session, to avoid creating expectations about changes that occurred between the practice and the test sessions.

After the second test session, participants were asked to respond to a questionnaire about the unexpected stimuli (provided in Appendix A). This questionnaire consisted in a yes-or-no question and a free recall question (to which participants might answer by writing or drawing) about the unexpected stimulus. The questionnaire also included two rating scales. Additionally, we included a question about the blocks during which the participants noticed the unexpected stimuli, for those who were aware of it. After answering the questionnaire, they were requested to continue performing the task and told that they could ask any questions at the end of the experiment. Before the last session, the experimenter required the participants to ignore the discs and to attend to the background patterns instead. During this session, the task was to respond to the diamond pattern. Participants were instructed that the discs and the square pattern were irrelevant for this new session.

Electrophysiological Recordings

EEG data were collected using a Geodesic Sensor Net with 256 Ag/AgCl electrodes and a high input-impedance Net Amps dense-array amplifier (Electrical Geodesics, Inc., Eugene, OR). Data were digitized at a sampling rate of 250 Hz. Sensors for horizontal and vertical electrooculograms (EOGs) were included in the EGI net. Impedance was kept below 50 kΩ. All electrodes were referenced to the vertex electrode (Cz) and were filtered on-line using a low-frequency cutoff of 0.1 Hz and a high-frequency cutoff of 100 Hz.

Data Analysis

Two participants were excluded due to technical problems during EEG recording. One participant answered “no” to the second questionnaire; but a debriefing after the experiment indicated that the participant had been aware of the patterns during the second block, despite answering “no” in the questionnaire. Because this suggested that the responses of this subject to the second questionnaire were unreliable, this participant was also excluded. Statistical analyses of behavioral and EEG data were conducted using the R software (R Development Core Team, 2017) and the SPSS Software v. 22.

Behavioral Analysis

For the main task, we analyzed reaction times in the main task. RTs above or below three standard deviations from the mean were excluded as outliers. This analysis was carried out only for sessions 1 and 2, as the task in session 3 was a different one.

All participants who drew or referred to a square in the free recall question were considered aware of the unexpected stimulus. Otherwise, participants were judged aware or unaware according to their response in the yes-no question and the rating scales: If they answered “no” to the yes-no question and rated three or less in the confidence rating and the frequency rating, they were considered unaware. Conversely, if they answered “yes” to the yes-no question or rated four or more in either the confidence rating or the frequency rating, they were considered aware.

ERP Analysis

EEG data was preprocessed using BrainVision Analyzer 2 software (Brain Products GmbH, Gilching, Germany). The EEG data was filtered with a Butterworth zero-phase filter with a low cutoff frequency of 0.53 Hz and a high cutoff frequency of 30 Hz, with a filter slope of 48 dB/oct for both cut-offs. 95 electrodes on the lower part of the head were excluded because they were subject to frequent muscle artifacts, in addition to five frontal electrodes.

For the remaining 156 electrodes, the continuous EEG data was segmented into trials starting at 100 ms before stimulus onset and ending at 600 ms after stimulus onset. We ran an automatic artifact detection procedure using the recording reference electrode Cz. The following criteria were employed for artifact rejection: trials were excluded in which the absolute voltage difference exceeded 50 µV between two neighboring sampling points, the amplitude was outside -100 or +100 µV, or the amplitude was lower than 0.5 µV during more than 100 ms in any electrode. On average, 13.96% of trials were excluded in artifact rejection. Data from two participants who had more than 33% artifact trials were excluded from further analysis. An electrode was marked as bad and excluded from the participant’s dataset if its amplitude exceeded the above thresholds in more than 10% of all trials. Electrodes that were excluded for this reason were replaced by a linear interpolation of the surrounding electrodes. Data from two participants were excluded from the analyses of session 3 due to problems during recording; for those analyses, a sample size of 28 was employed.

The EEG was averaged across trials and corrected to a -100 ms prestimulus baseline interval. All electrodes were re-referenced to an average reference. We selected the electrodes in the regions of interest (ROIs) corresponding to the ones used by Pitts et al. (2011):

Occipital ROI (Nd1): E119, E126, E116, E150, E117, E139, E118, E127;

Occipital-parietal ROI (Nd2): E85, E86, E87, E96, E97, E98, E99, E109, E108, E107, E141, E153, E162, E171, E170, E160, E161, E152, E151, E140.

We focused on the two components investigated by Pitts et al. (2011): (1) the negative component Nd1, in the window between 220 and 260 ms in the occipital region; and (2) the negative component Nd2 in the window between 300 and 340 ms in the occipital-parietal. We obtained the mean amplitude in the respective time windows and compared them using a mixed ANOVA with two within-subjects fixed factors: configuration (random vs. square) and session (1, 2, and 3); and one between-subjects random factor (aware vs. unaware group). We included session 3 in our analysis to investigate if our stimuli elicited ERPs related to texture segregation and awareness when participants focused their attention on them, we ran the same analyses on the data from session 3. We also compared P3 mean amplitudes between square and random configurations and across sessions to investigate if task relevance could be dissociated from awareness, as in Pitts et al. (2014). For the extraction of P3 amplitude we selected the time window between 350 and 550 ms. A ROI of 19 electrodes (E44, E185, E53, E144, E45, E132, E79, E80, E81, E131, E90, E89, E130, E143, E88, E100, E101, E129, E142) was chosen, corresponding to the electrodes in Pitts et al. (2014). For all tests, a significance level (α) of .05 was adopted.

Finally, we computed correlations between the mean amplitude differences for the Nd1 and Nd2 components and the responses to the square for the first awareness questionnaire. This aimed at replicating the results from Pitts et al. (2011), who observed positive correlations between Nd2 and awareness measures, but not between Nd1 and awareness measures.

Alpha Activity Analysis

We explored whether pre-stimulus alpha activity would be related to awareness at the behavioral level, as indicated by responses to the awareness questionnaire. We also investigated the relationship between alpha activity and contour integration and awareness at the electroencephalographic level, as indexed by the ERP components Nd1 and Nd2, respectively.

For these analyses, the continuous data were segmented from -500 to 600 ms relative to stimulus onset. Segments containing artifacts were rejected using the same criteria as for the ERP analysis. We used a fast Fourier Transform to extract alpha power in the interval (-500 to 600 ms) to obtain the power spectrum with a resolution of 1.95 Hz after applying a Hanning window of 10% of the interval length. Spectral lines between 7.5 and 13.5 Hz were summed to extract power in the alpha band. Because alpha activity is most prominent over the parieto-occipital sites, we selected 42 electrodes over that region: E101, E119, E126, E137, E129, E128, E127, E138, E142, E141, E140, E139, E149, E153, E152, E151, E150, E162, E161, E160, E159, E171, E170, E100, E110, E118, E88, E99, E109, E117, E125, E87, E98, E108, E116, E124, E86, E97, E107, E115, E85, E96.

We then performed the following comparisons. Initially, we compared alpha activity between the aware and unaware groups to investigate if the difference in awareness measured behaviorally would be reflected on a difference in alpha activity. Afterwards, we performed a median split of participants based on the power of the pre-stimuli alpha activity, resulting in two groups with high- and low alpha power. Then, we explored whether alpha activity is related to Nd1 or Nd2 by comparing the mean amplitudes of these components between alpha groups in the first session, when some participants were aware and others were unaware. At the trial level, we sorted single-trials ERPs by alpha power using a median split, resulting in a low trial-level alpha group and a high trial-level alpha group. Afterwards, we compared Nd2 mean amplitudes between square and random configurations and between trial-level alpha groups.

Results

Behavioral Results

RTs for correct responses in both configurations are shown in Table 4-1 for both groups.

Table 4-1

Means and standard deviations (in parentheses) of RTs by configuration, session, and awareness group, in ms

	Unaware group		Aware group	
Configuration	Session 1	Session 2	Session 1	Session 2
Square	643.24 (43.21)	638.45 (58.50)	651.56 (60.72)	636.24 (41.79)
Random	639.26 (49.77)	638.62 (56.04)	644.30 (44.54)	633.58 (50.67)

To test for the possibility that the background stimuli captured attention automatically, we ran a 2 x 2 x 2 ANOVA with RT as dependent variable, the within-subjects factors of configuration (random vs. square) and session, and the between-subjects factor of awareness group. No significant effects were observed for either configuration ($F(1,30) = 0.5$, $p = .49$), session ($F(1,30) = 1.0$, $p = .32$), or group ($F(1,30) = 0.01$, $p = .91$).

Table 4-2 shows the results for the awareness questionnaire. All participants from both groups were aware of the background square configuration during session 2.

Table 4-2

Results of the awareness questionnaire by session and group

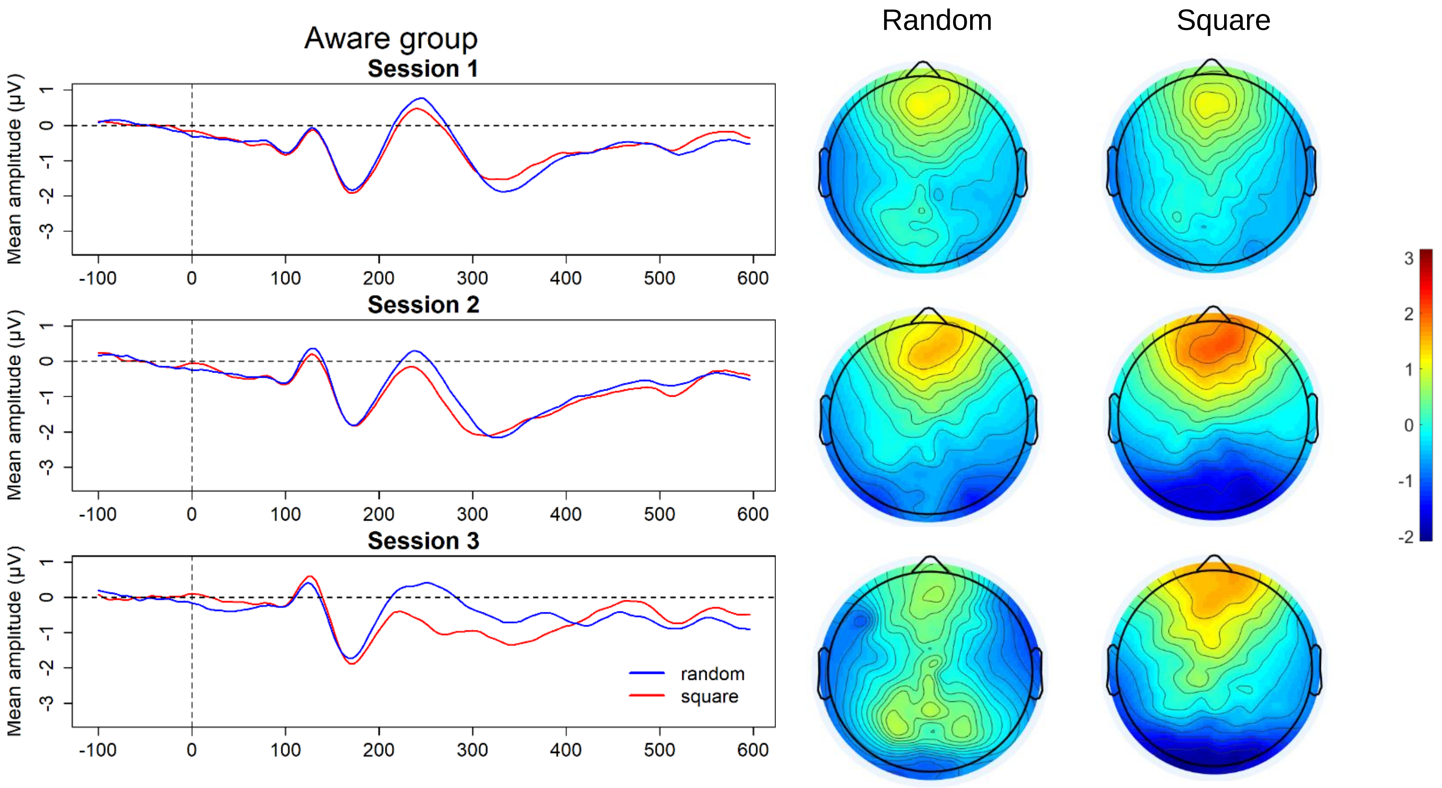
Group	N of participants who reported each shape			Mean confidence ratings						Mean frequency ratings					
	Square	Diamond	Neither	Diamond	Horizontal Rectangle	X Pattern	Square	Four Squares	Vertical Rectangle	Diamond	Horizontal Rectangle	X Pattern	Square	Four Squares	Vertical Rectangle
Session 1															
Unaware group	0	0	13	2.61 (1.32)	1.77 (1.01)	3.08 (1.04)	2.23 (1.48)	2.15 (1.21)	2.15 (1.46)	2.61 (1.32)	1.54 (0.66)	2.54 (1.26)	1.54 (0.66)	1.54 (0.88)	1.61 (0.87)
Aware group	14	6	3	3.35 (1.27)	2.00 (1.17)	3.12 (1.05)	4.17 (1.07)	2.41 (1.12)	2.70 (1.10)	2.82 (1.01)	1.65 (0.70)	3.23 (1.09)	3.47 (1.33)	1.88 (0.78)	2.35 (1.00)
Session 2															
Unaware group	13	8	0	4.15 (1.28)	2.15 (1.14)	2.08 (1.32)	4.92 (0.28)	2.15 (1.40)	1.92 (1.19)	2.77 (1.23)	1.54 (0.52)	1.77 (0.83)	4.31 (0.85)	1.61 (0.87)	1.38 (0.51)
Aware group	17	7	0	4.05 (1.43)	1.94 (1.03)	2.59 (0.87)	4.88 (0.33)	1.88 (1.05)	2.47 (1.12)	3.35 (1.22)	1.53 (0.62)	2.06 (1.09)	4.59 (0.51)	1.41 (0.51)	1.76 (0.90)

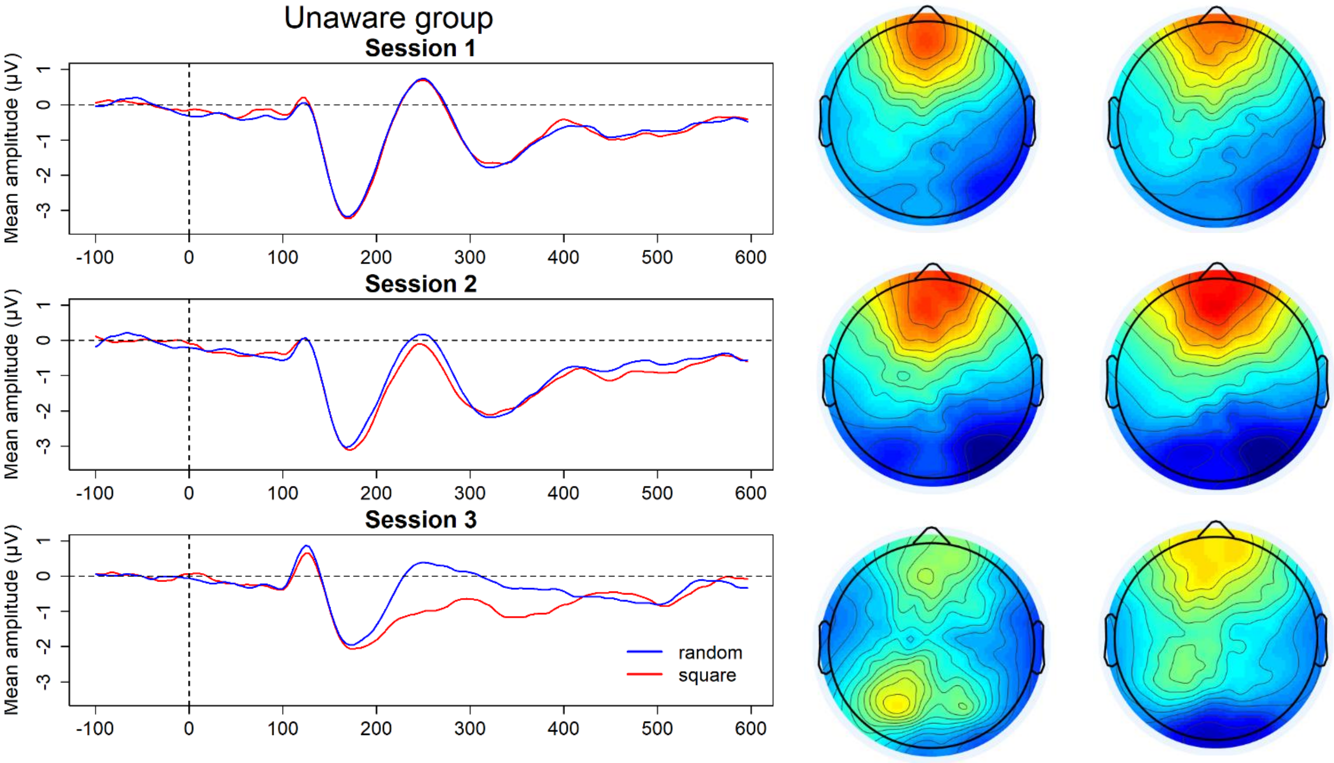
ERP Results

Grand averaged waveforms for both square and random configurations in sessions 1, 2 and 3 for both ROIs are shown in Figure 4-3 for the Nd1 and in Figure 4-4 for the Nd2.

Figure 4-3

Grand averaged waveforms and scalp maps for square and random configurations, separated by session and awareness group, for the Nd1 (220-260 ms)

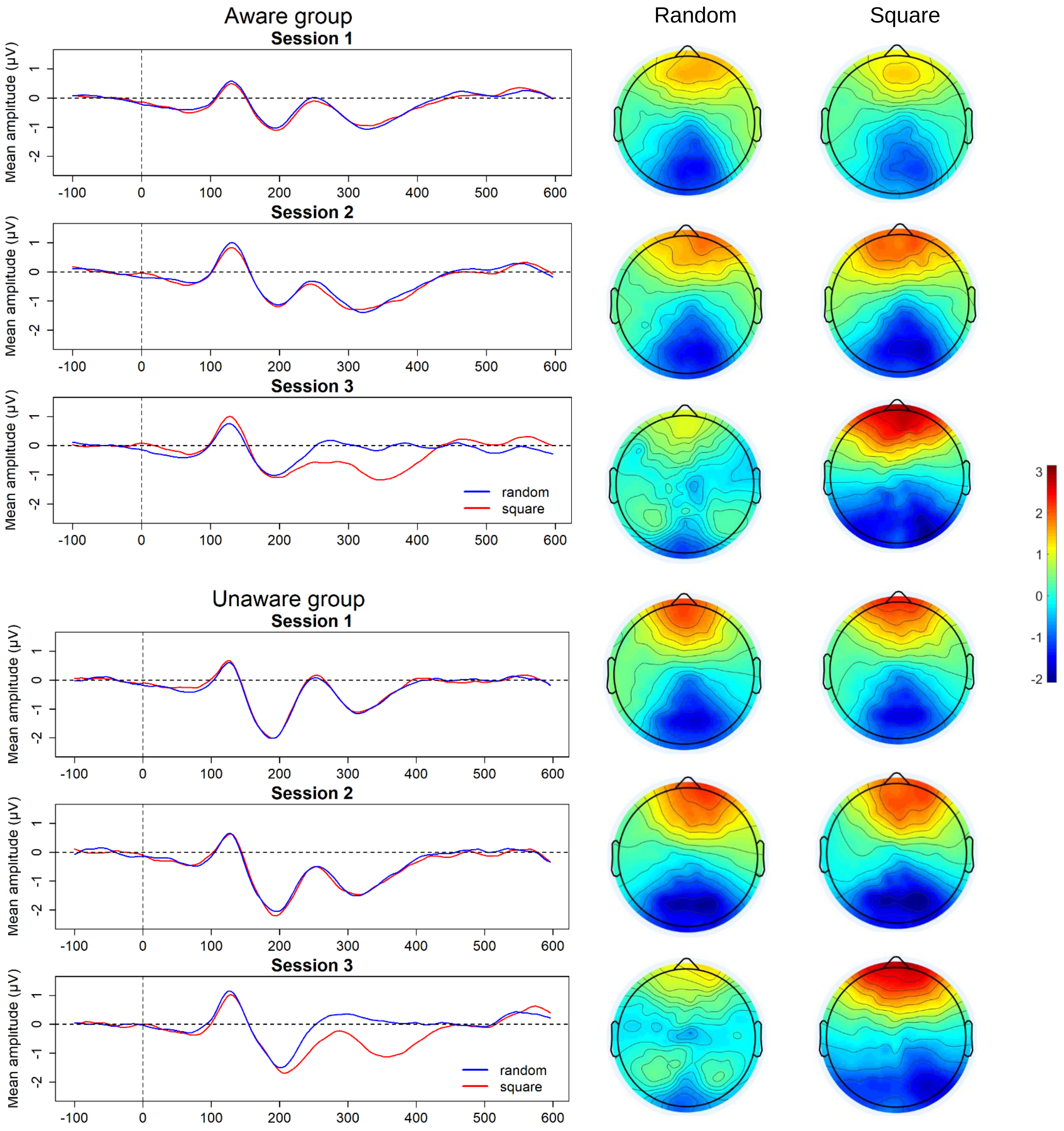




Means and standard deviations for the Nd1 and Nd2 by configuration, group, and session are plotted in Figure 4-5. A mixed ANOVA with the factors of configuration, session, and group, and Nd1 mean amplitude as dependent variable revealed a main effect of configuration, F(1,28) = 23.07, $p < .001$, $\eta^2_P = .452$; a main effect of session, $F(1,28) = 11.90$, $p = .002$, $\eta^2_P = .298$; and no effect of awareness group, $F(1,28) = 0.85$, $p = .363$, $\eta^2_P = .030$. In contrast to Pitts et al. (2011), we did find an interaction between configuration and session ($F(1,28) = 18.59$, $p < .001$, $\eta^2_P = .399$). There was no three-way interaction between configuration, session, and group ($F(1,28) = 1.27$, $p = .269$, $\eta^2_P = .043$). Follow-up comparisons showed a significant difference in Nd1 amplitude between the square and random configurations in sessions 2 ($t(29) = -2.80$, p = .009) and 3 ($t(29) = -5.37$, $p < .001$), but not in session 1 ($t(29) = -1.62$, $p = .116$).

Figure 4-4

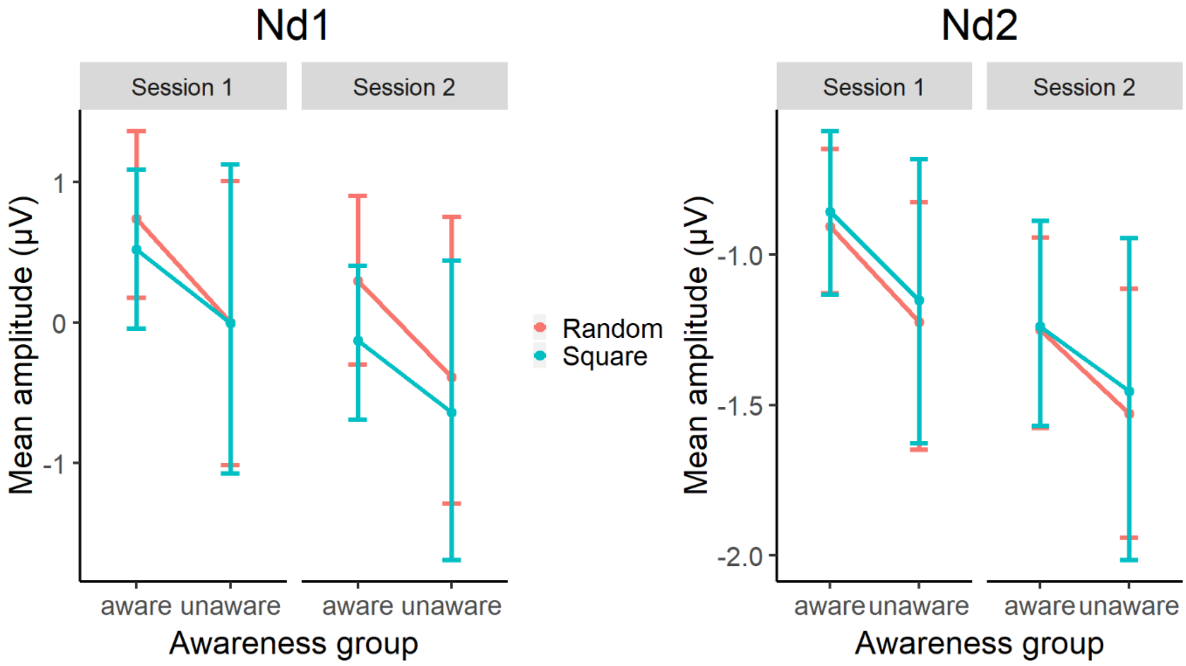
Grand averaged waveforms and scalp maps for square and random configurations, separated by session and awareness group, for the Nd2 (300-340 ms)



For the Nd2, we found a main effect of session (*F*(1,28) = 13.56, *p* = .001, η^2_P = .326), with significant differences between both sessions 1 and 2 (*p* = .003) and sessions 2 and 3 (*p* < .001). We also observed an effect of configuration (*F*(1,28) = 10.62, *p* = .003, η^2_P = .275), but no effect of group (*F*(1,28) = 0.58, *p* = .812, η^2_P = .002). There was an interaction between configuration and session (*F*(1,28) = 27.83, *p* < .001). Separate *t*-tests showed this interaction to be due to a difference between square and random configurations in sessions 3 (*t*(29) = -5.09, *p* < .001), but not in session 1 (*t*(29) = 0.58, *p* = .566) or session 2 (*t*(29) = 0.43, *p* = .669).

Figure 4-5

Mean amplitude for the Nd1 and Nd2 by configuration, session and awareness group. Data points are means; error bars are standard errors of the mean across 30 participants



Concerning P3 amplitude, a 2x3x2 ANOVA with configuration, session and group as factors showed a significant effect of configuration (*F*(1,28) = 45.86, *p* < .001, η^2_P = .621), with a larger P3 amplitude for square trials compared to random trials. There was also an effect of session (*F*(1,28) = 28.44, *p* < .001, η^2_P = .504), and no effect of group (*F*(1,28) = 1.13, *p* = .297, η^2_P = .039). Pairwise comparisons revealed that there was a significant difference between sessions 1 and 3 (*p* < .001) and sessions 2 and 3 (*p* < .001), but not between sessions 1 and 2. An interaction between configuration and session ($F(1,28) = 32.82$, $p < .001$, $\eta^2_P = .540$) was also present, with the configuration effect being present only during session 3. No other interactions were observed. Waveforms for the channels used in the analysis of P3 amplitude are shown in Figure 4-6.

Alpha Activity Results

We first compared mean alpha power between aware and unaware groups. This analysis did not show any significant differences between groups ($t(29) = 0.887$, $p = .382$). Then, we compared Nd1 and Nd2 mean amplitudes between alpha groups defined by the median split with an ANOVA with the factors configuration and alpha group. For the Nd1, no effects of alpha group ($F(1,28) = 0.05$, $p = .862$, $\eta^2_P = .002$) or configuration ($F(1,28) = 1.40$, $p = .241$, $\eta^2_P = .05$), and no interactions. For the Nd2, there was no effect of alpha group ($F(1,28) = 0.843$, $p = .366$, $\eta^2_P = .028$) or configuration ($F(1,28) = 0.60$, $p = .443$, $\eta^2_P = .02$); however, there was an interaction between configuration and alpha group ($F(1,28) = 6.71$, $p = .015$, $\eta^2_P = .182$). Post-hoc tests indicated that the difference between square and random configurations was present only in the low alpha group ($t(15) = 2.13$, $p = .049$), but not in the high alpha group ($t(15) = -1.39$, $p = .166$).

In the analysis of alpha power at the trial level, we ran an ANOVA with configuration and trial-level alpha group as factors and Nd2 mean amplitude as outcome. Results showed no effect of configuration ($F(1,28)= 0.65$, $p = .448$, $\eta^2_P = .02$), a significant effect of trial-level alpha group ($F(1,28)= 18.20$, $p < .001$, $\eta^2_P = .370$), and an interaction between configuration and trial-level alpha group ($F(1,28)= 6.02$, $p = .02$, $\eta^2_P = .163$). Follow-up tests showed that the difference between square and random configurations is present only in the high trial-level alpha group ($t(29) = 2.13$, $p = .05$), but not in the low trial-level alpha group ($t(29) = -1.39$, $p = .161$).

Lastly, we tested for correlations between the behavioral measures of awareness of the square in the first questionnaire and the differences between mean amplitudes of both the Nd1 and the Nd2 in the square and random configurations. In contrast with Pitts et al.’s (2011) results, we found no significant correlations between either measure with the Nd1 or the Nd2, except for a small correlation between responses to the frequency ratings and Nd1 mean amplitude. The correlations are shown in Table 4-3.

Figure 4-6

Grand averaged waveforms and scalp maps for square and random configurations, separated by session and awareness group, for the P3 (350-550ms)

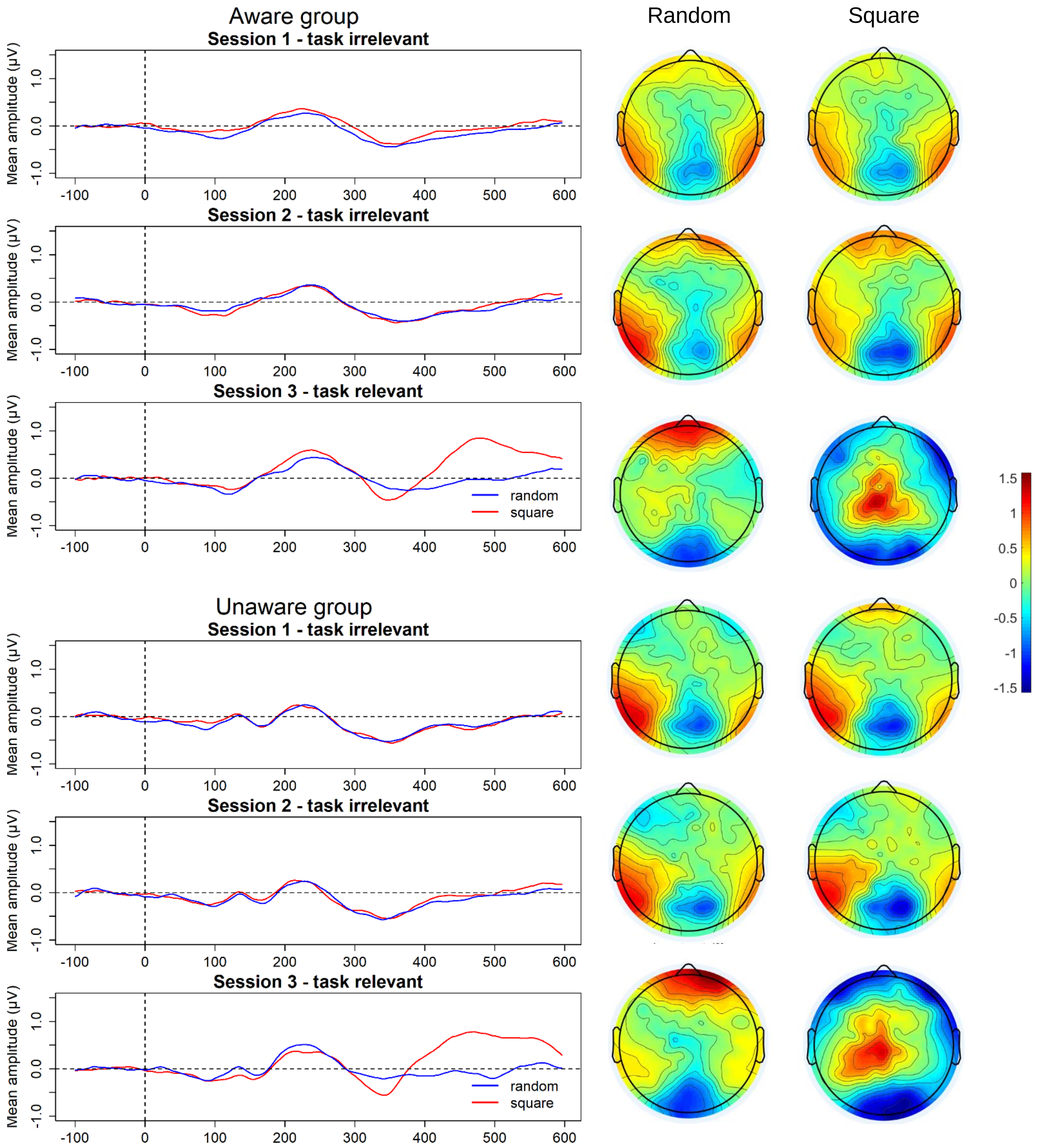


Table 4-3

Correlations between behavioral measures of awareness in the first questionnaire and awareness group, in ms

	Nd1		Nd2	
	r	*p*	*r*	*p*
Confidence ratings	-.161	.378	-.331	.065
Frequency ratings	-.446	.011	-.278	.124

Discussion

In this study, we replicated the results of Pitts et al. (2011) only partially. Crucially, we found no evidence for implicit texture segregation when subjects were unaware of the segregating stimuli, despite clear evidence for segregation when those the background patterns were task-relevant. Similar results on texture segregation have been reported elsewhere, using behavioral measures. Rashal et al. (2017), using the inattention paradigm (Russell & Driver, 2005), observed no implicit grouping of stimuli similar to those employed here and in Pitts et al. (2011). In a comparison experiment, they removed the background elements that did not belong to the square shape, effectively removing the need for texture segregation to form the shape. The results for that comparison experiment showed that participants did accomplish implicit shape formation. They suggest that attentional demands are a function of not only individual types of grouping, but of the specific operations that compose each type of grouping.

Regarding the results for the Nd2, we observed only an effect of session, but no effect of group. This effect of session might be due to participants becoming aware of the stimuli between the first and second sessions; however, given the lack of differences between groups, it might be simply be the result of repetition or habituation effects in the EEG responses. One possible explanation for this inconsistency in results is the fact that assessment of awareness was not performed on every trial, but only between blocks. For this reason, the two groups may have been mixed in the awareness of the background stimuli, which would lead to smaller differences in the Nd2 between them. Indeed, some participants in the aware group reported becoming aware of the unexpected stimuli only in the middle or near the end of the block, so that, for the most part, their Nd2 responses would be similar to those of the unaware group. We also did not observe any significant correlations between responses on the confidence and frequency ratings to the square and Nd2 mean amplitude.

Concerning the P3 analyses, we replicated the results from Pitts et al. (2014), who used the same data from Pitts et al. (2011) to show that awareness can be dissociated from task relevance at the EEG level. When participants focused their attention on the background stimuli, in session 3, a larger amplitude was observed for square trials compared to random trials; no such difference was detected in sessions 1 or 2. This was expected, since in session 3 the shapes were targets instead of the discs. This result also shows that the background stimuli, when task-relevant, elicit a normal P3 response.

Our analysis of alpha activity showed mixed results. Comparisons between alpha activity in the two awareness groups defined by questionnaire responses showed no significant results. However, comparisons between groups defined by alpha power showed differences in Nd2 mean amplitude. This result is consistent with the literature showing that low alpha activity indicates high attention and vigilance in participants.

With regard to the differences between the current experiment and the original study by Pitts et al. (2011), it is possible that less attention was available to the background in our study because task difficulty was kept constant throughout the entire session. The original study conducted by Pitts et al. (2011) employed a fixed decrement to the discs during the whole session. In this design, learning may occur over the course of a block, and consequently participants’ responses become may more automatized. In this case, more attentional resources would become available (“spill over”) to the background configurations. Supporting this explanation are the results of session 3 in our experiment, in which a large difference was observed between the configurations for both groups. The presence of a large effect of configuration in session 3, when participants focused their attention on the shapes, indicates that our manipulation was effective in eliciting distinct ERPs. Thus, the absence of implicit texture segregation in our study might be due to less attention being available to process background resources, which would imply that texture segregation cannot occur without attention.

A related explanation for the conflicting results is the difference in perceptual load between our study and Pitts et al. (2011). According to perceptual load theory, when the perceptual load of a task is high, less attention is available to be directed at the concomitant unrelated stimuli (Lavie et al., 1995; Lavie & Tsal, 1994; Macdonald & Lavie, 2008).

Converging evidence for this has been provided by studies showing reduced P1 and N1 waves evoked by distractors when the perceptual load of targets is higher (e.g., Couperus, 2009). In our experiment, we employed an adaptive procedure with a 50% target accuracy threshold. This made the task quite hard, as reported by our participants during debriefing. Our use of an adaptive procedure with such a threshold may have increased the perceptual load compared to the original study, resulting in little attention available for the background configurations. As in the discussion on learning effects and our use of an adaptive procedure to keep difficulty constant across the experiment, this would also imply that texture segregation actually requires attention. The fact that focused attention also acts to suppress irrelevant stimuli (Desimone & Duncan, 1995; Luck & Kappenman, 2012; Pitts et al., 2018) provides some plausibility to this explanation. This issue may be worth investigating in future studies.

A recent study seems to argue against the hypothesis that perceptual load was responsible for the absence of implicit texture segregation (Pugnaghi et al., 2020). In that study, a target number was presented on an imaginary circle surrounding a matrix of letters, and participants had to categorize that number as larger or smaller than 5. Perceptual load was varied by presenting seven other stimuli on the imaginary circles: in the low load condition, those seven stimuli were hashes (“#”), whereas in the high-load condition they were letters. The unexpected stimulus were numbers presented among the letters, which were in the same category (“congruent”) or in the opposite category as the target number. Implicit processing was assessed through the interference of the unexpected stimulus on the response to the target. In two experiments, no effects of perceptual load were observed, suggesting that perceptual load does not interfere with implicit processing. However, differences among that study and the present experiment complicate the comparison of the respective conclusions. Pugnaghi et al. (2020) examined the influence of perceptual load on interference at the response level, whereas we investigated processing at an early, perceptual level. In particular, response interference tasks engage distinct underlying processes, namely, inhibitory mechanisms (Forster et al., 2014). Furthermore, whereas the stimuli used in that study were similar to the targets, in our study they were clearly distinct. Similarity to the target is a factor that is known to influence the spread of attention to unexpected stimuli (Most et al., 2005), so this makes comparison between these studies difficult.

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CHAPTER 5. EFFECTS OF TEMPORAL EXPECTATIONS ON THE PERCEPTION OF MOTION GESTALTS

Manuscript under revision.

Nobre, A. P., Nikolaev, A. R., Gauer, G., van Leeuwen, C., & Wagemans, J. (2020). Effects of temporal expectation on the perception of motion Gestalts.

Abstract

Gestalt psychology has traditionally ignored the role of attention in perception, leading to the view that autonomous processes create perceptual configurations that are then attended. More recent research, however, has shown that spatial attention influences a form of Gestalt perception: the coherence of random-dot kinematograms (RDKs). Using event-related potentials (ERPs), we investigated whether temporal expectations exert analogous attentional effects on the perception of coherence level in RDKs. Participants saw fixed-length sequences of RDKs and reported the coherence level of a target RDK indicated by a post-cue. Target expectancy increased as the sequence progressed until target presentation; afterwards, no expectancy towards the following stimuli remained. Expectancy influenced the amplitudes of ERP components P1 and N1. Crucially, expectancy interacted with coherence level at the N1 but not at the P1. Specifically, P1 amplitudes decreased linearly as a function of RDK coherence irrespective of expectancy, whereas N1 exhibited a quadratic dependence on coherence: larger amplitudes for the most ambiguous (i.e., most difficult to perceive) RDKs with intermediary coherence levels, and only when they were expected. These results suggest that expectancy at early processing stages is an unspecific, general readiness for perception. At later stages, expectancy becomes task-relevant and selectively applies to ambiguous stimulus configurations.

Keywords: event-related potentials; expectation; Gestalt; motion; visual attention

Expectation is one of several processes that guide attention to visual stimuli (Zhao et al., 2013), wherein probabilities provide modulatory biases that guide perception (Nobre & Van Ede, 2018). Expectations are shaped by probabilities concerning spatial position, feature, or time (Nobre & Rohenkohl, 2014; Summerfield & Lange, 2014). In the latter case, also referred to as temporal expectation or temporal attention, temporal structure is used to prioritize and select items for processing (Nobre & van Ede, 2018). Temporal expectations have been investigated using cueing and foreperiods (Nobre, 2001; Summerfield & Egner, 2009; Nobre & Rohenkohl, 2014; Summerfield & Lange, 2014). These studies raise the question whether temporal expectation functions as a temporal analog to the direction of attention by spatial expectation (Nobre & Rohenkohl, 2014; Carrasco, 2018).

With spatial attention, we observe effects of enhanced perceptual resolution and detectability to the attended regions. For example, Carrasco and colleagues demonstrated that attention increases contrast sensitivity (Carrasco, 2006), perceived color saturation (Fuller & Carrasco, 2006) and perceived spatial frequency (Abrams et al., 2010). Event-related potential (ERP) studies show an effect of the attended region on the early visual responses, as early as C1, beginning at its point of onset (57 ms) (Kelly et al., 2008; Slotnick, 2018), P1 (peaking about 100 ms), and N1 (peaking about 200 ms) (Hillyard et al., 1998; Martinez et al., 2007).

Temporal expectation likewise influences sensory performance (Rezec et al., 2003; Burr et al., 2009; Rungratsameetaweemana et al., 2018; Nobre & van Ede, 2018). For example, Coull and Nobre (1998) observed that temporal cueing of “x” or “+” stimuli improved performance in a detection task. However, several ERP studies (Miniussi et al., 1999; Griffin et al., 2002; Doherty et al., 2005; Correa et al., 2006; Hackley et al., 2007; Correa & Nobre, 2008) found that, in contrast to spatial attention, temporal attention modulates the later ERP component N1, but not P1 or C1. This would suggest that mechanisms of expectancy influence perception in later stages compared to spatial attention.

Here we will study the effects of temporal expectation on the organization of dynamic Gestalt stimuli. The Gestalt tradition views coherent global motion as the product of common fate grouping (Yuille et al., 1988; Uttal et al., 2000; Stürzel & Spillmann, 2004). Gestalt theory attributed little importance to the concept of attention (Boring, 1929), and instead relied on mechanisms of figure-ground organization as a mechanism of selection (van Leeuwen et al., 2011). The neo-Gestalt tradition (e.g. Pomerantz, 1981) has understood this as implying that perceptual organization, and more specifically perceptual grouping, occurs preattentively and that attentional effects take place only after grouping has been achieved (Kahneman & Henik, 1981; Duncan, 1984; Julesz, 1991).

In line with this view, a more recent model (Levinthal & Franconeri, 2011) proposes that motion directions across the visual field are processed in parallel, based on common fate. This process produces a map of regions, wherein each region is assigned a direction. Attention, according to this model, can select only one common-fate group at a time. Activation peaks in the selected map correspond to all locations where elements move in the selected direction. Based on those peaks, objects that move in the same direction can be grouped by common fate, therefore appearing to move together.

Nonetheless, behavioral evidence challenges the notion of preattentive grouping. For example, Rezec et al. (2003) found that manipulating spatial expectations by spatial cueing Random-Dot Kinematograms (RDKs) reduced coherence thresholds in a direction discrimination task. This notion of preattentive grouping would be further undermined in ERPs if expectation effects were found to occur as early as P1. Some evidence suggests that temporal expectation does modulate P1 when combined with spatial orienting (Doherty et al., 2005), but also that expectation may influence early stages of perception when certain conditions are met, e.g., when task demands are high (Correa et al., 2006). Accordingly, the neo-Gestalt view has currently been replaced by the view that principles of grouping operate at multiple stages and at multiple levels (Wagemans et al., 2012), based on neurophysiological evidence for the dynamical organization of perceptual experience (van Leeuwen et al., 2011). The dynamical framework allows for complex interactions between grouping and selection, based on attention and/or expectancy. For instance, in MEG, anticipatory (pre-stimulus) effects of cueing were found in the right V1 and cuneus, as well as early and late effects on evoked activity (Plomp et al., 2010). Thus, in particular, an effect of expectancy on early evoked visual potentials, including P1, might arise.

We use ERPs to consider the role of temporal expectations in the processing of coherent motion. ERP studies found that the evoked components about 200 ms after motion onset (N200 or N1) reflect the coherence level in motion stimuli (Aspell et al., 2005; Niedeggen et al., 2006; Martin et al., 2010). For example, the amplitude of the N200 increases linearly with perceived coherence (Niedeggen et al., 2006). Attentional modulations of coherent motion have also been observed in this time window (Niedeggen et al., 2002;

Niedeggen et al., 2004; Niedeggen et al., 2006), as well as in later visual processing (Kau et al., 2013). No effects on P1 were reported, however.

Despite clear evidence that attention modulates processing of moving stimuli starting from the N1, several shortcomings must be highlighted regarding the conclusions that can be drawn from the previous studies. First, whereas previous ERP studies on coherent motion (Niedeggen et al., 2002, 2006; Martin et al., 2010) indicate that attention influences perception of coherent motion, they employed a few or only 2 coherence levels: completely random (0% coherence) and completely coherent (100% coherence) RDKs (e.g., Kau et al., 2013). Nevertheless, employing a full range of coherence levels is important to investigate more global motion processing based on grouping and Gestalt formation. For example, discrimination of motion direction in 100% coherent RDKs can be performed using only local motion signals, since every dot has the same local motion vector (Cai et al., 2014). Intermediary coherence levels, on the other hand, demand global integration for discrimination of direction. Moreover, attention may have distinct effects within the range of coherence levels because of increasing non-linearity across the hierarchy of the visual system (Norcia et al., 2015). At lower levels in the hierarchy, visual processing leading to perception of coherent motion, for example, may only slightly deviate from linearity. Correspondingly, attentional effects may be straightforward. However, when the result of low-level processing propagates to higher levels, further non-linear operations are applied to the signal (Alp et al., 2017) and attentional influences may become non-additive. The relationship between the amount of allocated attention and the degree of motion coherence has not been examined before.

Second, although some of the attentional paradigms employed in previous studies of coherent motion are related to temporal attention, their occurrence is contingent on other factors. For example, motion blindness (Niedeggen et al., 2002, 2004) has been interpreted as resulting from a limitation in the ability to redirect attention from one stimulus to another given short SOAs (Niedeggen et al., 2006), which is similar to what occurs in the psychological refractory period (Pashler, 1994). If so, this paradigm imposes demands beyond the selection aspects of attention and might not reflect the same mechanisms that operate in the context of the temporal structure of tasks, which are observed with manipulations such as foreperiods or cueing (Nobre & Van Ede, 2018). The pattern of results reported in those studies might not be observed when such additional demands are absent.

Thus, thorough demonstrations of systematic relationships between expectation and coherent motion perception are still missing. In the current study, we investigated the role of temporal expectations in the perception of coherent global motion in a parametric stimulus space. To this end, we independently manipulated the coherence levels of the RDKs and the amount of participants' attention to motion coherence, both of which were varied in small steps. We collected participants' reports of the perceived coherence of RDKs, as well as ERPs. Two intervals after motion onset were considered, which are defined by 2 major ERP components: P1 and N1. This allowed us to construct a common space of neurophysiological and phenomenological responses, which represents gradual relationships between attention and motion coherence with a precision level that has not been achieved before.

To manipulate temporal expectation, we apply a method related to the foreperiod technique (Ambinder & Lleras, 2009). We present trials comprising of sequences of 10 RDKs, one of which is a target. The probability of target occurrence in a sequence (i.e., hazard rate; Nobre & Rohenkohl, 2014) varies across sequences, and each sequence necessarily contains one target. Hence, the probability of any RDK being the target increases as the sequence progresses, given that the target has not yet appeared. Consequently, expectation towards the target gradually increases with the RDK's position in the sequence until target presentation (Ambinder & Lleras, 2009), after which target expectation is gone. Therefore, by comparing ERPs for RDKs in distinct positions within the sequence, we can examine how increasing expectation influences perception of coherent motion. The target is indicated by a post-cue (Thibault et al., 2016), since a pre-cue would modify participants' temporal expectation towards a target (Summerfield & Lange, 2014), leading to an interference with our manipulation of expectancy through stimulus position.

We also include some methodological precautions to rule out possible confounds. Task demands influence attention and expectation effects on perception-related ERP components, in particular P1 (Handy & Mangun, 2000; Correa et al., 2006). In our study, by employing target and distractor RDKs that were drawn with equal frequency from the same set of coherence levels (see Methods), and by using a demanding discrimination task with high uncertainty about the target instead of a detection task, we ensure that participants need to keep focusing their attention throughout trial. This increases the likelihood of observing possible attentional effects on the P1.

Furthermore, the task-relevant feature influences the relationship between attention and coherent motion. For example, the patterns of hemodynamic activation and ERPs are distinct when participants attend to motion direction and motion coherence (Kau et al., 2013). This might occur because judgement of simple features, such as direction of motion, is supported by cortical areas that are lower in the visual hierarchy than those involved in judgement of motion coherence. This would lead to distinct latencies of modulation by attention. This is especially important for our study given that attending to specific features modulates the effects of attention on early ERP components, such as the P1 (Zhang & Luck, 2009). In our experiment, participants perform a task in which they focus on the level of motion coherence, instead of orthogonal features such as direction. Hence, our design would increase the probability of finding early (e.g., at the P1 latency) effects of attention on coherent motion perception.

Methods

Participants

A power analysis was performed before data collection to determine the sample size for the study, based on previous studies showing a $\eta^2_p = 0.26$ for the difference between amplitudes of random and coherent RDKs in the motion-related N1 (e.g., Martin et al., 2010). Assuming an alpha of .05 and a power of 0.80, this resulted in a sample size of 26. We collected data from 3 more participants to ensure a sufficient sample size given a loss of 2-3 participants due to preprocessing of EEG.

Twenty-nine healthy adults participated in the experiment. All conformed to the following inclusion criteria: no psychiatric or neurological disorders (self-reported), no use of any medication or alcohol prior to the experiment, and normal or corrected-to-normal vision. Data from 2 participants were excluded due to excess of EEG artifacts (as described below), leaving 27 participants (10 male) aged 20-30 years (mean = 23.8, SD = 2.6). All participants provided written informed consent. The study was approved by the Ethics Committee of the Faculty of Psychology and Educational Sciences of KU Leuven.

Stimuli and Experimental Design

The stimuli were RDKs in which some dots moved coherently in the same direction across frames for the whole stimulus duration (signal dots), while others (noise dots) moved in random directions in between frames (Scase et al., 1996). Throughout the entire presentation of the RDK, the same dots were the signal dots, while the remaining dots were noise dots (“same rule”; Scase et al, 1996). The percentage of signal dots defined the coherence level of an RDK, which varied between 0% and 100% in steps of 10. To prevent participants from tracking individual dots, all dots had limited lifetimes (Saenz et al., 2002). Dots that drifted beyond the boundary of the RDK field were replotted in a random location in the field, to keep the number of dots in the field constant across frames. Noise dots moved following a Random Walk algorithm (Scase et al., 1996), so that, in each frame, noise dots were assigned a random direction while keeping the same speed, instead of being replotted on the screen in each frame. This avoids any possible confounds of systematic sudden onsets on the early ERPs.

RDKs were presented at the center of the screen within a circular region with a radius of 7.35 dg of visual angle against a uniform grey background (11.2 cd/m^2 luminance). The following parameters were used for the RDKs: number of dots: 720; dot field area: 678.86 dg^2; dot density: 1.06 dot/ dg^2; dot size: 0.05 × 0.05 dg; dot contrast: 3.6875 (Weber contrast); dot luminance: 52.5 cd/m^2; dot speed: 13 dg/s; dot lifetime: 4 frames. These parameters were kept constant throughout the experiment.

Within a trial, a sequence of RDKs was presented in the rapid serial visual presentation (RSVP) paradigm. A trial comprised one target RDK, pseudorandomly embedded in a sequence of 9 distractor RDKs, with the restriction that consecutive RDKs could never have the same coherence level, although 2 RDKs with equal coherence could be presented in the same trial in non-consecutive positions. The coherence levels of target and distractors RDKs were randomly drawn from the same uniform distribution of coherence levels. Thus, targets (and distractors) were presented the same number of times in each position across the experiment. Coherence level and direction of motion varied across trials.

A target RDK was indicated by an auditory cue with a frequency of 350 Hz and a duration of 48 ms, which followed the target with an onset jitter of 0 to 50 ms drawn from a uniform distribution. The sound served as a post-cue to direct the participant’s attention retroactively to the target.

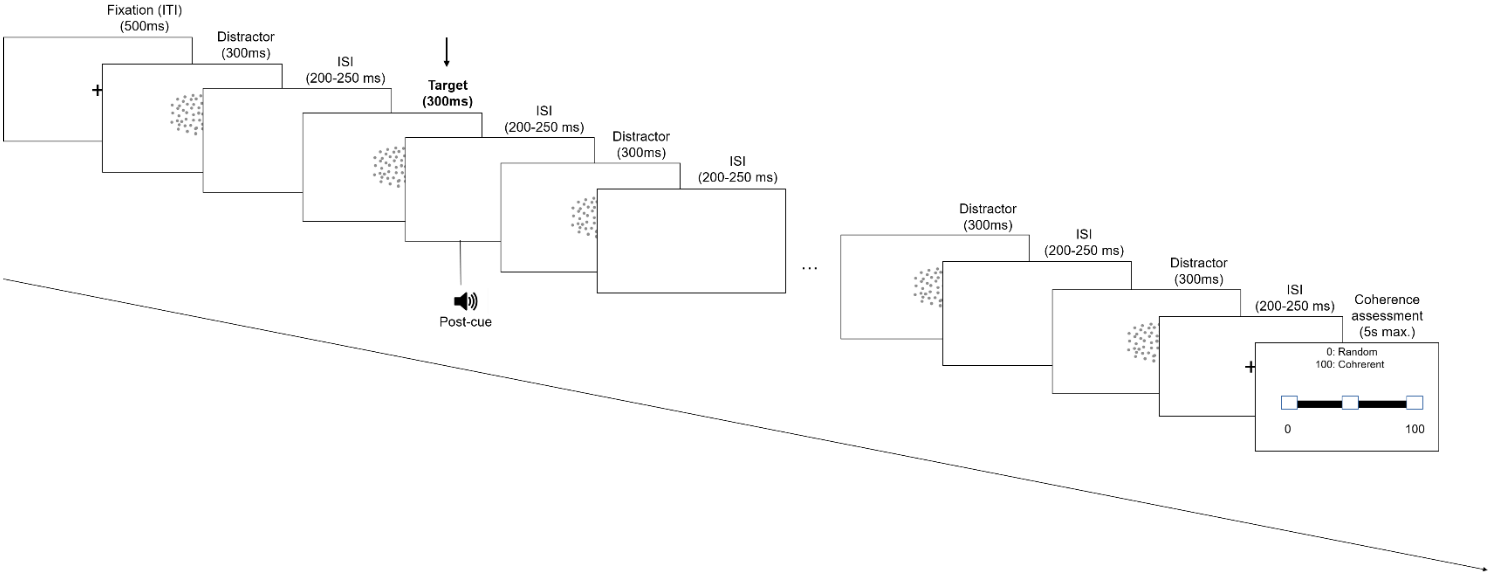
Procedure

Participants were seated in front of a 24.1 in LCD Monitor screen (1920 x 1200 resolution, 60Hz refresh rate, Eizo FlexScan S2410W), at a distance of 70 cm. Stimulus presentation and registration of keyboard responses were performed with custom software programmed in Python using the PsychoPy library (Peirce, 2009; Peirce & MasAskill, 2018). A chinrest was used to control the position of the participant's head. Participants were requested to keep fixating at the center of the screen. They were instructed that, in each trial, a series of stimuli would be presented sequentially, with one of those stimuli being followed by a sound (post-cue). The task for the participant was to report the coherence level of the target. Assessment of participants' responses was performed at the end of a trial. At the response screen a bar labeled "random" at the left end and "coherence" at the right end was presented. Participants were asked to indicate the perceived coherence level by moving the cursor along the response bar using 2 arrow keys - one to move the cursor to the left, and another one to move the cursor to the right, and to confirm their choice by pressing the central down arrow key. Participants had up to 5 seconds to respond. In case of timeout, they were requested to respond faster in the following trials. Trials with timeout were discarded from the analysis.

A trial started with a fixation cross at the center of the screen, which lasted for 500 ms (Figure 5-1). Afterwards, the presentation of RDKs began. RDKs were presented for 296 ms, with an ISI jittered between 200-250 ms, resulting in an SOA of 496-546 ms. Such stimulus duration and ISI were chosen to reduce overlap between epochs in the time window of interest, since the N1, in which we were interested, peaks at around 200 ms post-stimulus (Niedeggen et al., 2006; Luck, 2014). A cue was presented between RDKs, during the ISI. The cue's start time was jittered during the ISI, ranging from 50 to 100 ms. An inter-trial interval (ITI) of 500 ms was employed, during which a fixation cross was presented at the center of the screen. Each participant completed 600 trials, for a total of 6000 RDK stimuli. Hence, there were 600 targets at each stimulus position, balanced across 10 levels of coherence; 600 targets at each coherence level, balanced across stimulus positions; and 60 targets of identical coherence at each stimulus position.

Figure 5-1

Experimental design for one trial



A practice session with 20 trials was performed before the EEG session to ensure that participants understood the task. During this practice, participants received feedback on every trial to ensure that they correctly understood the task. The feedback consisted of presenting the participant's response error: the absolute value of the difference between the participant's response and the target's true coherence level.

EEG recording

EEG was continuously recorded throughout the experimental session using a Geodesic Sensor Net with 256 Ag/AgCl electrodes, amplified through a high input-impedance Net Amps amplifier (EGI, a Philips company, Eugene, OR, USA) using the Net Station software. The electrode montage included sensors for recording vertical and horizontal electrooculogram (VEOG and HEOG). Data were digitized at a sampling rate of 250 Hz. Impedance was kept below 50 kΩ. All channels were referenced to the vertex electrode (Cz) and were preprocessed on-line using a low-frequency cutoff of 0.1 Hz and a high-frequency cutoff of 100 Hz.

Behavioral Analysis

For the behavioral analysis, we considered two dependent variables: coherence ratings for each coherence level and cue location; and accuracy, quantified as response errors: the absolute difference between coherence rating and true coherence for a given stimulus.

To investigate if participants' sensitivity to differences in coherence level changes across cue locations, we analyzed the slopes of coherence ratings by true coherence level for each cue location. Our hypothesis was that, if expectation increases sensitivity to coherence, slopes of coherence rating by coherence level should be steeper for later than for early cue locations.

In the analysis of accuracy, we compared response errors between cue locations separately for each coherence level. The reason for this was that, because of the fixed length of the response bar, the possible maximum error systematically depends on coherence levels. Additionally, response scales such as the one employed here are susceptible to bias by the central tendency of judgment (Hollingworth, 1910). Such bias influences points along the scale to a distinct degree, precluding direct comparisons of accuracy between coherence levels.

EEG Analysis

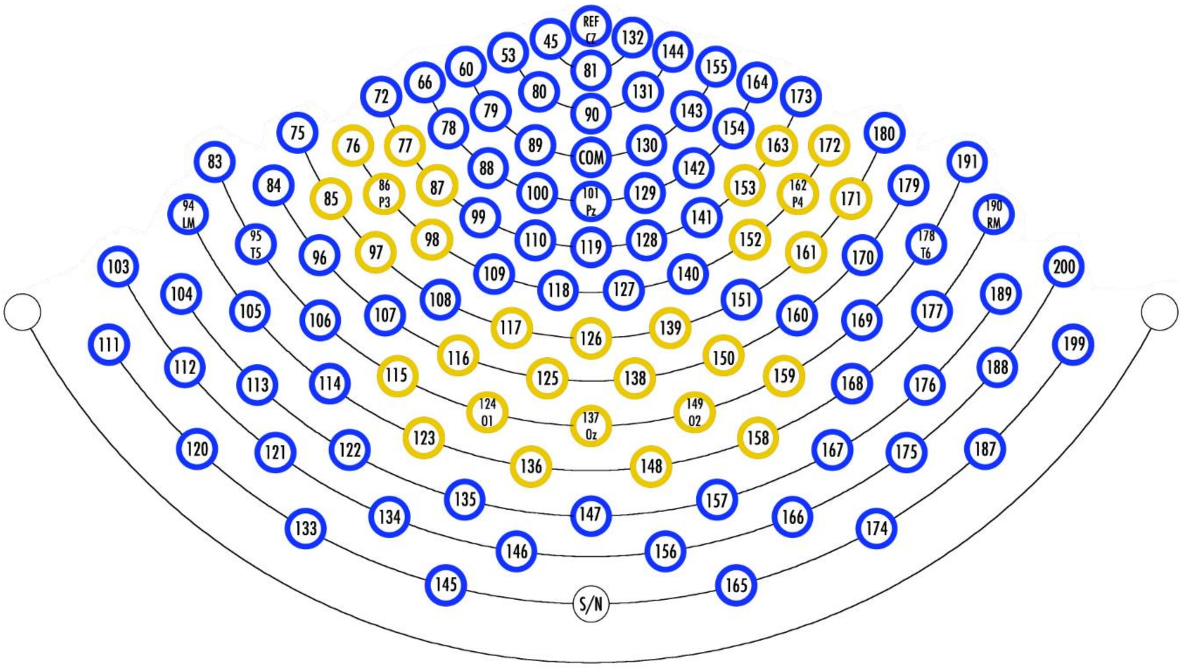
EEG was analyzed using BrainVision Analyzer 2 software (Brain Products GmbH, Gilching, Germany). The EEG data were filtered with zero phase shift Butterworth filters of the 2nd order with a low cutoff frequency of 0.5 Hz and with a high cut-off of 30 Hz, with a filter slope of 12 dB/oct for both cuttoffs, and a 50 Hz notch filter. We removed 95 of 256 electrodes on the cheeks and neck, which showed strong muscle artifacts or poor contacts, and retained the data from the remaining 161 electrodes for further analyses.

We visually inspected EEG channels and excluded the ones that appeared to be noisy by visual inspection and the ones which were indicated as bad during recording by Netstation. We derived the vertical and horizontal EOG, respectively, as the difference between the activity of electrodes placed above and below the eyes and of the ones placed near the right and left outer canthi of the eyes. We segmented EEG in epochs from -100 to +300 ms relative to stimulus onset. To identify bad channels, we employed an automatic artifact detection procedure. The following criteria were employed for artifact detection: the absolute voltage difference exceeded 50 µV between 2 neighboring sampling points; the amplitude was outside -100 or +100 µV; or the maximal difference in amplitude within an epoch exceeded 100 µV in any channel. If the percentage of excluded epochs for a particular channel exceeded 3%, the channel was removed. Next, we used ICA to correct for oculomotor and other artifacts. The removed channels were interpolated using spherical spline interpolation across the channel set. Then, EEG epochs were submitted to the artifact detection procedure using the same criteria as for detection of bad channels reported above. Epochs that matched any of the criteria were excluded (on average, 0.87% of epochs). The data were re-referenced to the average reference and baseline corrected using the interval from -100 to 0 ms relative to stimulus onset and were then averaged across epochs. The average number of epochs per condition entering the EEG analysis after artifact rejection is provided in Supplementary Tables S5-1 to S5-3.

We chose time windows for ERP analysis based on inspection of the grand average across all participants and conditions. We selected a time window for the P1 from 120 to 160 ms after RDK onset and for the N1 from 160 to 200 ms after the RDK onset and used the mean amplitude in these windows in the analyses. For the analysis of P1 and N1, 30 electrodes were selected a priori over the parietal and occipital areas in which the effects of attention on motion perception were observed in previous studies (Niedeggen et al., 2004, 2006; Martin et al., 2010). We selected 6 electrodes around P3 and P4 and 14 electrodes around O1, Oz, O2 electrodes of the International 10-20 System of Electrode Placement (Figure 5-2). ERPs were averaged over the 30 electrodes.

Figure 5-2

The subset of posterior electrodes of the 256-channel EGI HydroCel Sensor Net used in the experiment. Electrodes selected for the analysis are highlighted in yellow



Statistical Analysis

For the behavioral analysis, we focused on two factors: 1) coherence level: the percentage of dots moving in the same direction, ranging from 0 to 100 in steps of 10; and 2) cue location: the temporal location of the cue in the RSVP stream, from 1 to 9. Cue location 0 was excluded because it was preceded by a longer pre-stimulus interval and therefore was qualitatively distinct from other locations.

For the analysis of ERPs, we first examined the effects of expectation with the following factors as fixed effects: 1) expectancy vs post-expectancy condition: all epochs within a trial that were presented before the sound cue (expectancy, when participants expected a target), vs all epochs after the sound cue (post-expectancy, when no expectancy was present); 2) and stimulus position: the position of an epoch in the RSVP stream, from 1 to 9 (we excluded position 0 because it was only present in the expectancy condition, and was not affected by the overlap from previous events, making it qualitatively different from other positions). Afterwards, we assessed the effects of expectation on the perception of coherence, using the following factors: 1) expectancy vs post-expectancy condition, as above; and 2) coherence level: the percentage of dots moving in the same direction, ranging from 0 to 100 with a step of 10.

For statistical analysis, we built linear mixed models with participants as a random effect. We ran ANOVAs on the models to investigate the effects of the factors above, reporting likelihood ratios for all tests. An alpha of 5% was adopted for all significance tests.

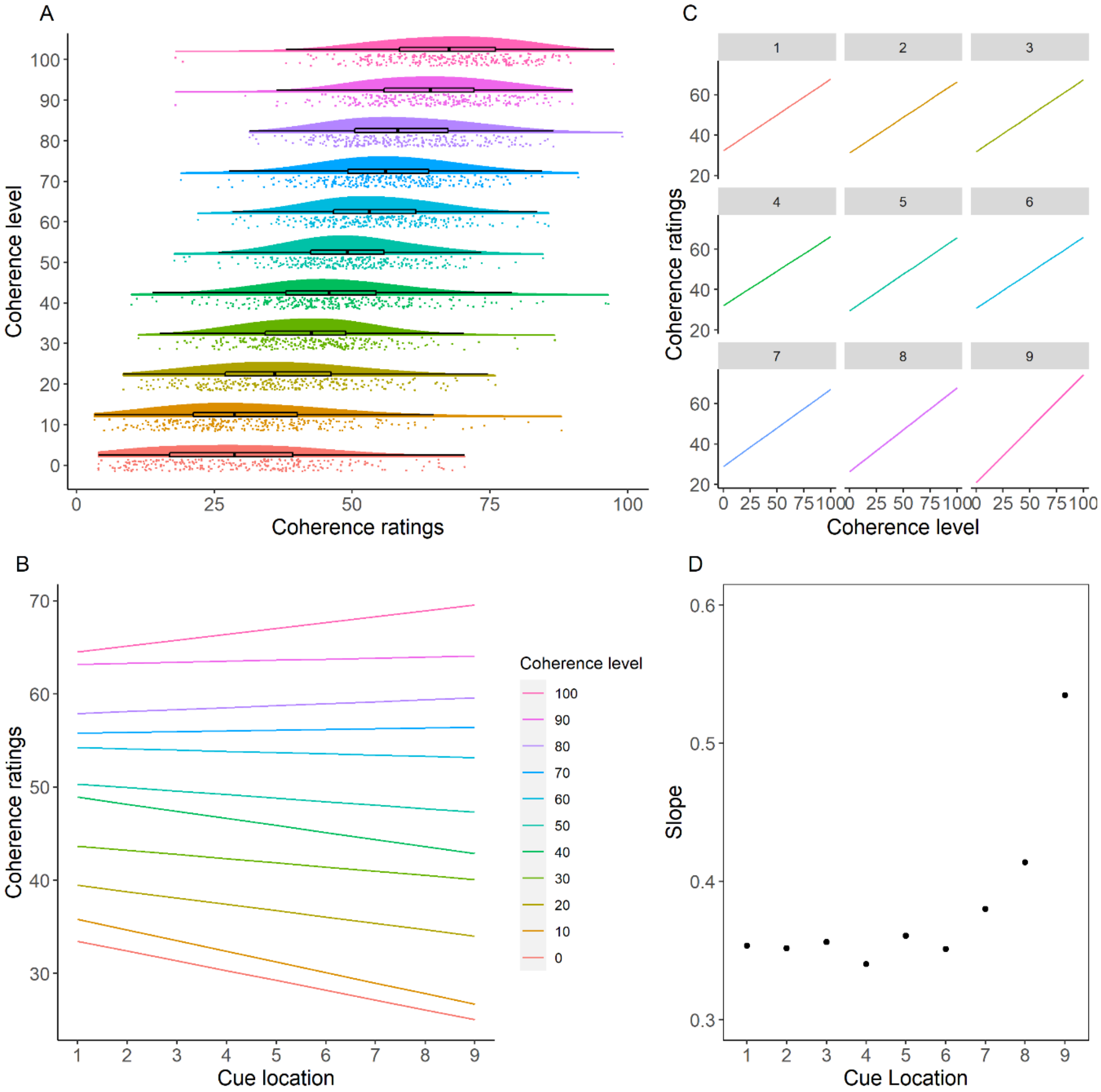
Results

Behavioral Results

The responses to the coherence of the target RDK (coherence ratings) are presented in Figure 5-3. Participants were able to discriminate between targets with distinct coherence levels (Figure 5-3A). An ANOVA with coherence rating as dependent variable and factors of coherence level and cue location showed an increase in coherence ratings with cue location, $F(9, 189) = 2.83$, $p = .004$; an increase in coherence rating with coherence level, $F(10, 210) = 64.98$, $p < .001$; and an interaction between cue location and coherence level, $F(90, 1890) = 2.22$, $p < .001$. This interaction is illustrated in Figure 5-3B and C, which shows a dependency of coherence rating on coherence level for each cue location. The slopes of linear fits for later cue locations were steeper than for earlier ones (Figure 5-3C and D).

Figure 5-3

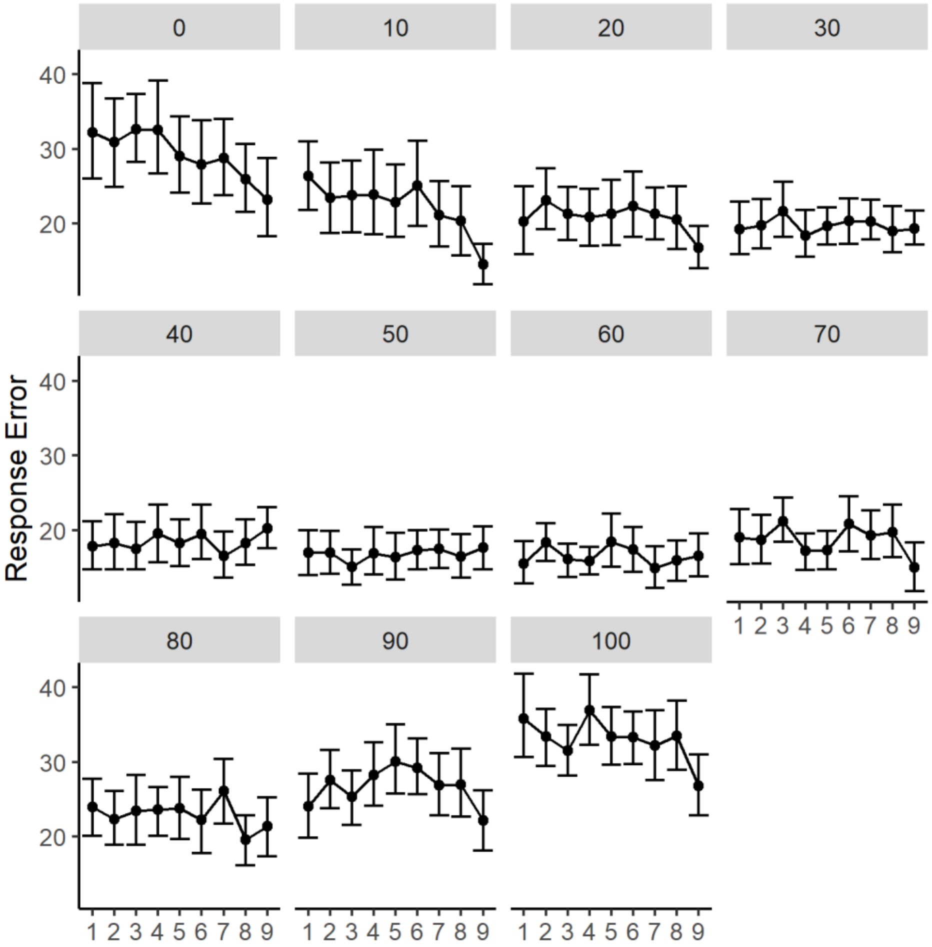
Coherence ratings to the target. A. Raincloud plots (Allen et al., 2019) of coherence ratings by coherence level of the stimulus, collapsed across cue locations. For each coherence level, the plot depicts the probability density of coherence ratings, raw coherence rating values (data points, one point for each cue location and each participant), and a boxplot showing median and interquartile range of the coherence ratings distributions. B. Coherence rating by cue location, separated by coherence levels. C. Coherence rating by coherence level for each cue location (indicated in the header of each panel). D. Point estimates of linear slopes for coherence rating as a function of coherence level for each cue location



To further investigate if discrimination improved with expectancy, we compared response errors using an ANOVA including only cue location as factor, since errors are not comparable between coherence levels (see “Behavioral analysis” above). The ANOVA revealed a significant effect of cue location ($F(8, 25) = 6.63$, $p < .001$). Planned comparisons with linear contrasts for each coherence level showed that cue location had an effect ($p < .001$) only for coherence levels 0, 10, and 100. As seen in Figure 5-4, error decreases with cue positions only for stimuli with high or low coherence, but not for those with intermediate coherence.

Figure 5-4

Response errors by cue location, separated by coherence level. Data points are means; error bars are standard errors of the means across 27 participants



ERP Results

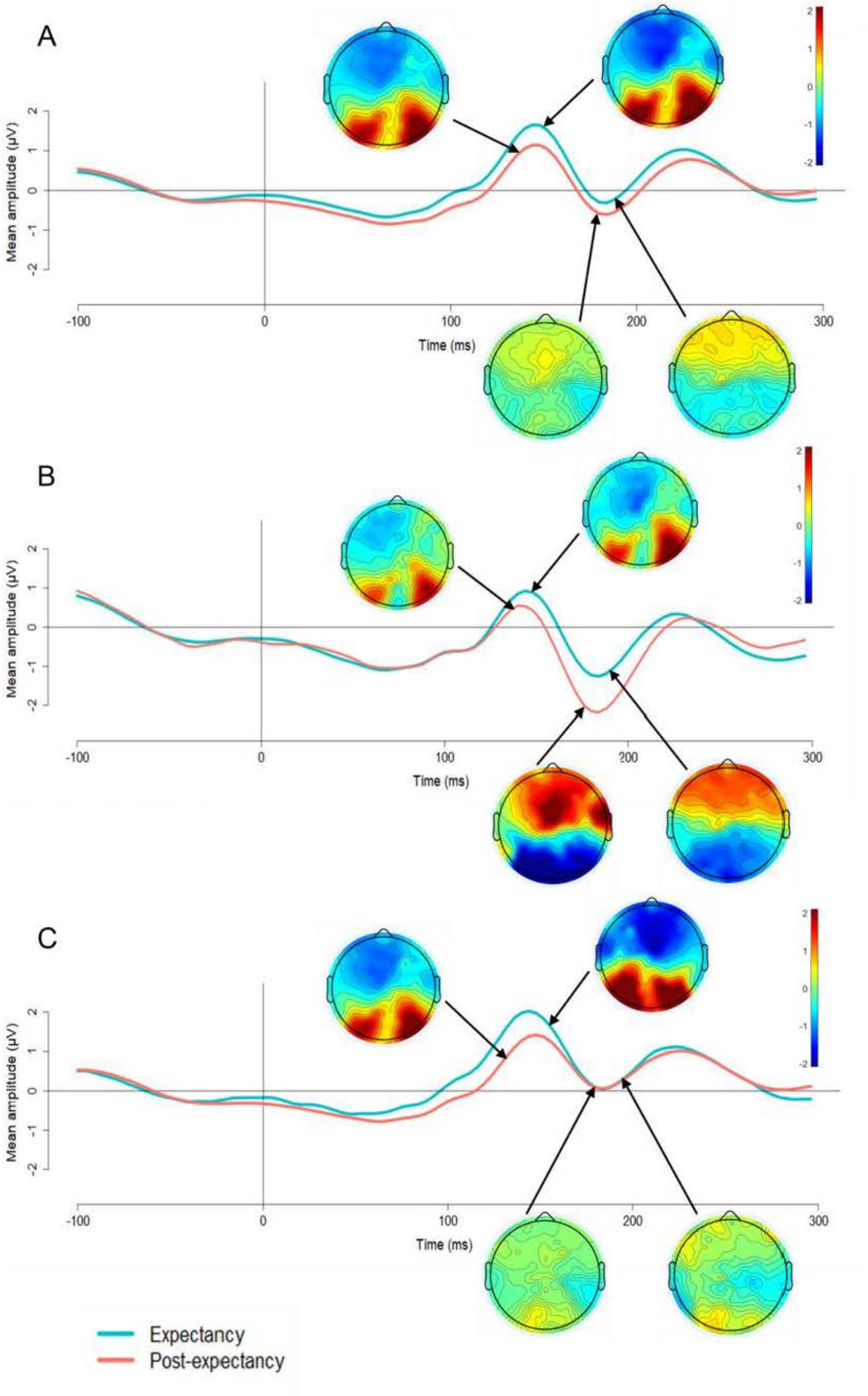
In the following sections, we first describe the effects of expectation on P1 and N1 amplitudes. Then, we describe how those effects interact with coherence levels to address our main question about influence of expectation on Gestalt perception of motion.

Effects of Expectation

Figure 5-5 shows the grand averaged ERPs and maps for expectancy and post-expectancy conditions for all stimulus positions pooled (A) and for examples of early (1st, B) and late (8th, C) stimulus positions.

Figure 5-5

Grand averaged ERP amplitudes for the electrode cluster used and voltage maps at 140 ms and 180 ms for expectancy and post-expectancy conditions. A: all stimulus positions pooled; B: stimulus position 1; C: stimulus position 8



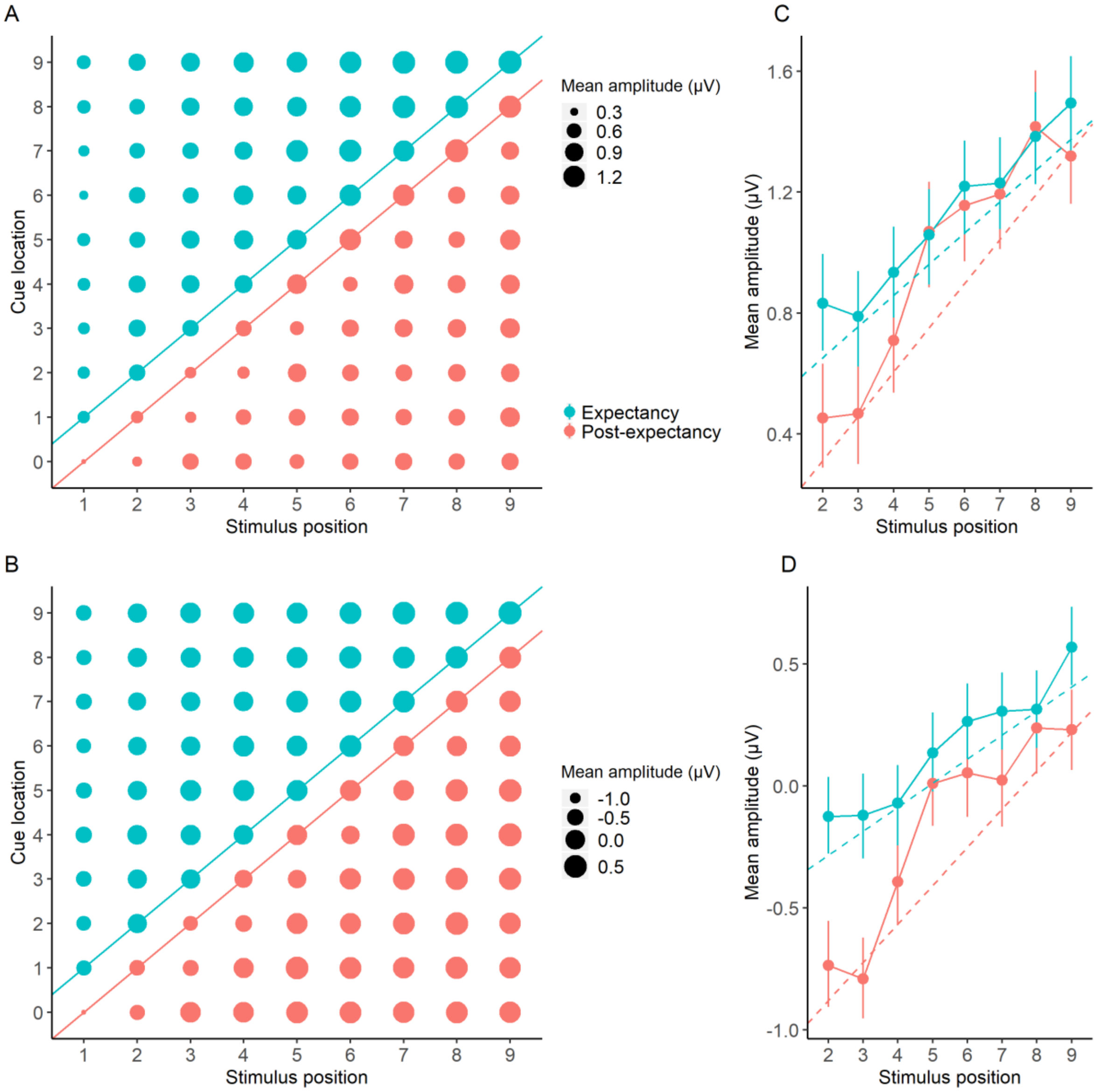
To test whether our manipulation of expectation had an effect on P1, we compared the P1 amplitudes between the expectancy and post-expectancy conditions for 9 stimulus positions. An ANOVA with the factors of expectancy (2 levels) and stimulus position (9 levels) showed that the P1 amplitude was significantly larger in the expectancy than in the post-expectancy condition, $\chi^2(4) = 332.70$, $p < .001$. We also found an effect of stimulus position, with P1 amplitudes increasing with stimulus position, $\chi^2(13) = 188.39$, $p < .001$. The interaction between stimulus position and condition was not significant, $\chi^2(21) = 11.38$, $p = .18$ (Figure S5-1A).

The same analysis on the N1 amplitude showed a significant effect of expectancy condition, with smaller N1 amplitudes for expectancy stimuli than post-expectancy stimuli, $\chi^2(4) = 109.12$, $p < .001$. The effect of stimulus position was also significant, $\chi^2(13) = 239.12$, $p < .001$. In contrast to the P1 results, we found an interaction between expectancy condition and stimulus position, $\chi^2(21) = 85.33$, $p < .001$, due to a difference between the expectancy and post-expectancy conditions at the early but not late stimulus positions (Figure S5-1B).

To examine the fine distribution of ERP amplitudes depending on stimulus position and cue location, we built matrices of P1 (Figure 5-6A) and N1 (Figure 5-6B) amplitudes by stimulus position × cue location. For both the P1 and the N1, we observed a clear diagonal trend: the amplitude changed from early to later epochs and from early to later positions of targets occurrence. In the follow-up analysis, we compared P1 and N1 amplitude between 2 diagonals: one corresponding to the last expectancy epochs before the cue (the targets) and another corresponding to the first post-expectancy stimulus after the cue, for each level of stimulus position from 1 to 9. The means and linear fits for each diagonal are shown in Figure 5-6C and Figure 5-6D.

Figure 5-6

Grand averaged ERP amplitudes in a matrix of stimulus position x cue location A: P1 amplitudes. B: N1 amplitudes. Expectancy and post-expectancy conditions are color-coded, and amplitudes are size-coded. The mean amplitude at the diagonal slices for P1 is given in C and for N1 in D, in which the dashed lines show linear fits. Data points are means; error bars are standard errors of the means across 27 participants



An ANOVA on the P1 amplitude with expectancy condition (represented by the diagonals in this model) and stimulus position as factors showed an effect of expectancy condition, $\chi^2(4) = 24.42$, $p < .001$, an effect of stimulus position, $\chi^2(18) = 224.32$, $p < .001$, and no interaction, $\chi^2(18) = 13.76$, $p = .06$, although the slope of the linear fit was smaller in the expectancy ($\beta = 0.103$) than the post-expectancy condition ($\beta = 0.146$) (Figure 5-6C). For the N1, we also observed an effect of expectancy condition, $\chi^2(13) = 109.15$, $p < .001$, and an effect of stimulus position, $\chi^2(12) = 162.61$, $p < .001$. However, in contrast to the P1, the interaction was prominent, $\chi^2(21) = 29.38$, $p = .003$, also with the smaller slope in the expectancy ($\beta = 0.124$) than the post-expectancy condition ($\beta = 0.186$) (Figure 5-6D). For both P1 and N1 the slopes converged, i.e., the effect of expectation on ERP decreased with the stimulus position.

To investigate the irregular increment with stimulus position visible in the curves (Figure 5-6C and Figure 5-6D), we conducted a post-hoc analysis between adjacent stimulus positions within each expectancy condition by testing consecutive contrasts (a t-test adjusted for multiple comparisons with the Tukey correction). The results were similar for P1 and N1. Only in the post-expectancy condition we found significant differences between stimulus positions 4 and 5 ($t(182) = 2.93$, $p = .02$) for P1, and between positions 3 and 4 ($t(182) = 3.02$, $p = .02$) and positions 4 and 5 ($t(182) = 2.90$, $p = .03$) for N1. In the expectancy condition, none of the comparisons were significant. The results for the P1 and the N1 are shown in Supplemental Tables S5-4 and S5-5, respectively.

Effects of Motion Coherence

Stimulus positions were aggregated for this analysis. A linear mixed model ANOVA with the factors of coherence level (11 levels) and expectancy condition (2 levels) showed an effect of coherence on P1 amplitude, $\chi^2(14) = 149.81$, $p < .001$: the amplitude decreased with increasing coherence level (Figure 5-7A). There was an effect of expectancy condition, $\chi^2(15) = 51.47$, $p < .001$, however, expectancy condition and coherence did not interact, $\chi^2(25) = 7.59$, $p = .66$, in contrast with the N1 results (see below). To characterize the effect of coherence on P1, we tested the linear, quadratic, and cubic contrasts for coherence levels separately for the expectancy and post-expectancy conditions. Only the linear contrast showed significant results in both the expectancy and post-expectancy conditions (Table 5-1).

Figure 5-7

ERP amplitudes for 11 coherence levels by expectancy condition. A: P1 amplitudes. B: N1 amplitudes. Data points are means; error bars are standard errors of the means across 27 participants. The dashed lines show linear and quadratic fits

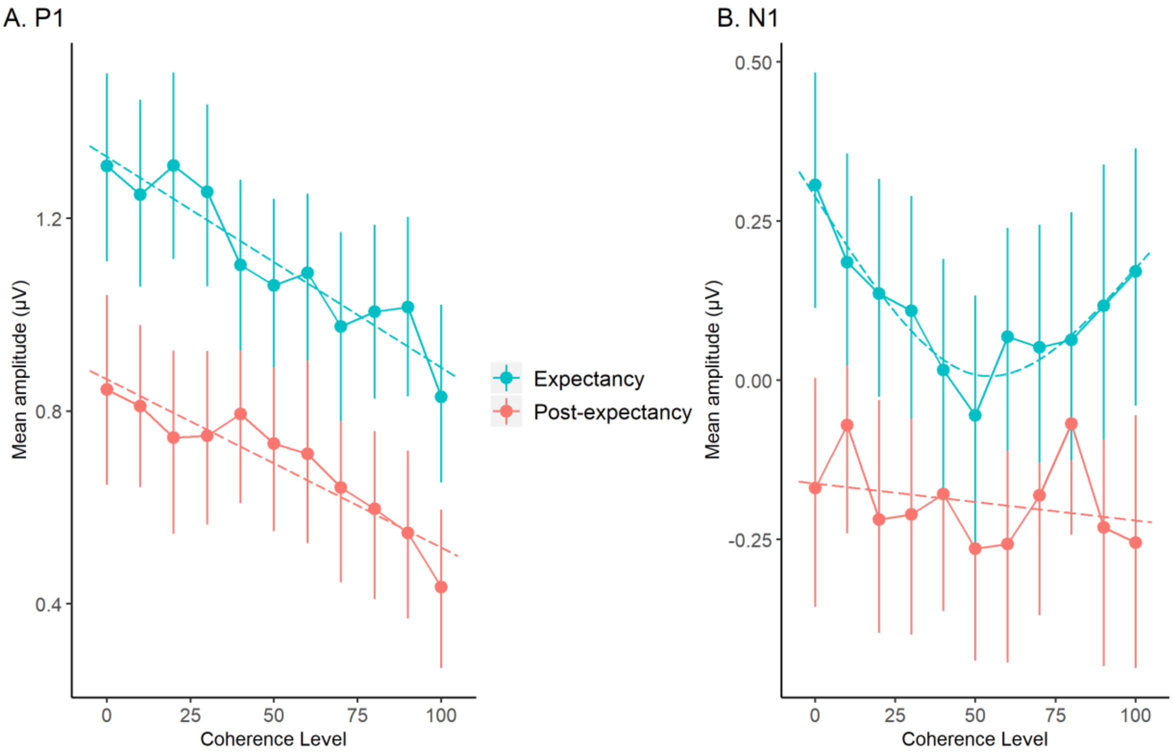


Table 5-1

P1 contrasts for coherence levels for expectancy and post-expectancy conditions

Condition	Degree	Estimate	SE	t-ratio	*p*
Post-expectancy	linear	-3.882	0.427	-9.087	**.001**
	quadratic	-1.710	1.194	-1.432	.632
	cubic	-0.159	2.674	-0.060	1.000
Expectancy	linear	-4.759	0.415	-11.462	**.001**
	quadratic	0.153	1.159	0.132	1.000
	cubic	-0.402	2.591	-0.155	1.000

The same ANOVA on N1 amplitude also showed an effect of coherence, $\chi^2(14) = 67.11$, $p < .001$ and an effect of expectancy condition, $\chi^2(15) = 109.40$, $p < .001$ (Figure 5-7B). In contrast to the P1 results, there was an interaction between coherence and expectancy condition, $\chi^2(25) = 25.51$, $p = .004$. The contrast analysis revealed a significant result for the linear contrast for both the expectancy and post-expectancy conditions. The quadratic contrast showed a significant result for the expectancy condition only (Table 5-2).

Table 5-2

N1 Contrasts for coherence level separately by expectancy and post-expectancy conditions

Condition	Degree	Estimate	SE	t-ratio	*p*
Post-expectancy	linear	-0.75	0.419	-1.790	**.037**
	quadratic	2.77	1.172	2.363	.104
	cubic	-1.86	2.624	-0.708	.980
Expectancy	linear	-1.35	0.406	-3.317	**.005**
	quadratic	7.52	1.134	6.630	**.001**
	cubic	-2.06	2.535	-0.812	.961

Discussion

We investigated how expectation influences the Gestalt perception of motion stimuli and its neural correlates. Participants were presented with series of Random Dot Kinematograms (RDKs), one of which was signaled as a target by an auditory post-cue. RDK coherence varied randomly across 11 levels. The participants' task was to report the coherence level of the target RDK. By varying the position of the auditory post-cue within the RDK series, we manipulated participants' temporal expectation toward the target: expectation gradually increased with the stimulus position until the cue and then suddenly dropped afterwards. To investigate the time course of influences of expectation on the neural correlates of Gestalt motion perception, we compared mean amplitudes for the P1 and N1 ERP components evoked by RDKs with different coherence levels and in distinct locations within the stimulus sequence.

The behavioral results indicate that coherence ratings changed with the position of the target RDK within the RDK stream. Crucially, this change occurred in the opposite direction depending on coherence level: coherence ratings increased with cue location for high coherence levels and decreased with cue location for low coherence levels. Consequently, slopes of coherence rating by coherence level were larger for later cue locations than for early cue locations. Analysis of response errors mirrored the results for coherence rating: errors decreased with cue locations, but only for extreme coherence levels.

Although the behavioral results seem to suggest that discrimination of intermediate-coherence RDKs does not benefit from expectation as much as totally random or totally coherent RDKs, this may be simply because of the central tendency bias (Hollingworth, 1910). This precludes definitive conclusions about the influence of expectation on the perception of coherence based on behavioral results. Therefore, we focus on ERP results to explore that influence in detail.

Effect of Expectation on ERPs

Before the cue, target expectation gradually builds up with stimulus position within a trial (a series of 10 RDKs) and more or less abruptly decreases after the cue. Since P1 amplitude and N1 amplitude generally increase with attention (Hillyard et al. 1998), such a manipulation of expectation should be manifested in amplitude changes in the ERPs in the expectancy condition only, not in the post-expectancy condition. However, the amplitudes of both the P1 and the N1 became more positive with stimulus positions in both the expectancy and post-expectancy conditions. This effect is evident in the matrices of amplitude by cue location vs. stimulus position shown in Figure 5-6A and B and was confirmed statistically in the analysis of diagonal slices of ERP amplitudes at the boundary between the expectancy and post-expectancy conditions within the matrices. Notably, the size of this effect is larger than that of coherence, as demonstrated by the different scales of Y-axes in Figure 5-6 and Figure 5-7.

Such similar patterns of changes in the expectancy and post-expectancy conditions are unlikely to be the consequence of our manipulation of expectation. Instead, we propose that they are related to an increase in cortical excitability, as a result of a rhythmic presentation of attended stimuli (Schroeder & Lakatos, 2009; Mathewson et al., 2012). However, whereas the amplitude of P1 gradually increased, the amplitude of N1 (a negative component) gradually decreased with stimulus position (Figure 5-6C, D). This suggests that different processes are associated with changes of these components. Whereas P1 may reflect increasing excitability, N1 may reflect increasing adaptation. The N1 is known to have a refractory nature: N1 amplitude decreases in response to repeated stimuli at the same attended location (Luck, 2014). Thus, the predominant P1 and N1 changes with stimulus position may reflect a background effect of the rapid serial visual presentation (RSVP) on the brain state, which occurs both with and without expectation.

Nevertheless, both the P1 and the N1 were sensitive to expectation. This is evident from the difference in P1 and N1 amplitudes between the expectancy and the post-expectancy conditions in the analysis of matrix diagonal slices. We propose that the observed effect of temporal expectations is supported by a modulation of cortical excitability by rhythmic stimulation (Schroeder and Lakatos 2009) in both expectancy conditions. Indeed, the entrainment of oscillations to a rhythmic structure of sensory inputs functions as a mechanism supporting temporal expectation and attention (Schroeder & Lakatos, 2009; Mathewson et al., 2012; Cravo et al., 2013).

Notably, the slopes of the linear fit for the expectancy and the post-expectancy conditions converge as stimulus position increases for both P1 and N1. This convergence is reflected in an interaction between expectancy condition (expectancy vs. post-expectancy) and stimulus position. For the P1, there was no interaction: at this stage, expectation simply boosts perceptual analysis, irrespective of stimulus position. This may be interpreted as a moderation of sensory gain processing by expectation (Hillyard et al., 1998; Luck & Kappenman, 2012), which does not vary with stimulus probability.

For the N1, the interaction occurs due to the steeper amplitude decrease with stimulus position in the post-expectancy condition compared to the expectancy condition. The steeper decrease in the post-expectancy condition is accompanied by stepwise changes between adjacent stimulus positions. In the first half of the trial, stepwise changes occur for both P1 and N1 until stimulus position 5, where the amplitude curves almost intersect (Figure 5-6C, D). This suggests that the effect of expectation on ERP reaches a ceiling in the middle of the trial. Similar ceiling effects were observed in behavioral studies exploring temporal orienting of attention in the “attentional awakening” (Ariga & Yokosawa, 2008; Ambinder & Lleras, 2009): performance in a discrimination task first increases with the position of the stimulus in a rhythmic sequential presentation and then reaches an asymptote. The authors propose that this effect arises due to the time it takes to synchronize internal attentional oscillations to the rhythmic stimulation so as to maximize perceptual processing by “attentional pulses” entrained to the stimuli (Large & Jones, 1999), and show that the magnitude of this effect is modulated by foreperiod expectation (Ambinder & Lleras, 2009). Here, we show a similarly shaped trend at the neural level when expectation is present, suggesting that similar mechanisms underlie both patterns of results.

Previous reports on the effect of expectation on P1 are inconsistent. Whereas some studies found such an effect (Correa et al., 2006; Rohenkohl et al., 2014), other studies indicated that P1 is not affected by temporal expectation (Miniussi et al., 1999; Griffin et al., 2002; Doherty et al., 2005; Correa & Nobre, 2008). The effect of expectation on P1 in our study might arise from the distinctive features of our experimental design. First, our experiment employed post-cuing of RDKs in an RSVP paradigm, which distinguishes it from more common manipulations of temporal attention and expectation, such as variations of foreperiods (Correa & Nobre, 2008). Different manipulations of expectancy lead to distinct effects on ERPs (Nobre & Rohenkohl, 2014). Furthermore, moderation of P1 amplitude by expectation may depend on the perceptual demands of the task (Correa et al., 2006), which in our experiment were high. Finally, in contrast to other experiments (e.g., Aspell et al., 2005; Martin et. al, 2010), coherence level was a task-relevant feature in our experiment. Attending to the coherence level leads to activation of higher-tier parietal areas, which are involved in the integration of motion components, compared to attending to other motion features, such as speed (e.g., Kau et al., 2013). Thus, one possibility is that the elevated cortical excitability, the difficulty of the task, and the task-relevance of the coherence level shift visual processing in our experiment to earlier stages. Conversely, the finding that expectation reduces the amplitude of the N1 reproduces the pattern observed in previous studies (Lange et al., 2003; Doherty et al., 2005; Correa et al., 2006; Hackley et al., 2007; Seibold & Rolke, 2014).

Effect of Motion Coherence on ERPs

P1 amplitude decreases linearly with increasing coherence level (Figure 5-7A). This indicates that processing of motion coherence is reflected in P1. The dependence of coherence level on ERP amplitude in the P1 time window –120 to 160 ms after onset of the RDK – indicates that this time is sufficient to process motion coherence. This time is earlier than it was reported before: motion coherence is typically reflected in M/EEG about 200 ms after the motion onset (Aspell et al., 2005; Niedeggen et al., 2006; Martin et al., 2010; Kau et al., 2013). This latency shift may occur because the elevated excitability, as proposed above, increases sensitivity to motion coherence.

In contrast to the linear relationship for the P1, the relationship between N1 amplitude and coherence level is about linear in the post-expectancy condition only. In the expectancy condition, a quadratic fit adequately describes the dependence of N1 amplitude on coherence level (although a linear trend is significant and is clearly visible for the coherence levels from 0 to 50 in Figure 5-7B). This finding indicates particular visual processing of intermediate coherence levels, in line with a TMS study, which found the larger effect of TMS application on the MT+ area for perception of RDKs of intermediate coherence compared to fully-coherent RDKs (Cai et al. 2014). However, it contradicts previous results showing that the ERP amplitude at the latency of 200 ms increases linearly with increasing coherence (Nakamura et al., 2003; Aspell et al., 2005; Niedeggen et al., 2006). Differences in design make it difficult to compare our results with those studies. Whereas our participants discriminated coherence level, Aspell et al. (2005) asked their participants to discriminate the direction of motion. In Nakamura et al.'s study (2003), participants watched a fixation point continuously without performing any other task. Compared to our stimuli, Niedeggen et al. (2006) and Nakamura et al. (2003) employed RDKs with much larger areas and shorter (Niedeggen et al., 2006) or longer (Nakamura et al., 2003) durations. Large stimuli reduce thresholds for coherent motion detection (Morrone & Vaina, 1995) and facilitate center-periphery interactions in perception of coherence (Habak et al., 2002). RDK duration interacts with coherence level in tasks where subjects need to discriminate RDK direction, producing shifts in accuracy that vary with coherence level (Pilly & Seitz, 2009). It is possible that these differences are responsible for the discrepancies with our results.

Effect of Expectation on the Perception of Coherent Motion

Our key findings concern relationships between expectancy conditions and coherence level for the P1 and the N1. For the P1, we found a main effect of expectation but no interaction between expectation and coherence level. Conversely, for the N1 we found both the main effect of expectation and interaction (Figure 5-6). The distinct effects of expectation on P1 and N1 allow us to dissociate 2 stages of coherent motion perception.

The first stage, indicated by the P1, includes processing of physical and Gestalt features of the motion stimulus, as indicated by the gradual brain responses to the gradual changes in the stimulus property, i.e., the coherence level. While expectation does affect the

P1 stage, as evidenced by the main effect of expectancy condition (Figure 5-6A), the effect of expectation at this stage, instead of reflecting selective attention, may be understood as a general readiness for perception (Nobre & Rohenkohl, 2014; Serences & Kastner, 2014) in the visually demanding RVSP paradigm. The enhanced readiness in expectancy condition may result in higher arousal, which increases P1 amplitude (Vogel & Luck, 2000). This effect is non-specific, in the sense it does not depend on the configuration of the stimulus, and thus do not vary with coherence level. In our design, this general readiness increases along a trial sequence and leads to linear changes in P1 amplitude with stimulus probability.

At the second stage, indicated by the N1, the effect of expectation becomes more specific, deploying selective attention instead of general readiness mechanisms. At this stage, expectation interacts with the processing of motion coherence. This disturbs the linear relationships between stimulus properties and brain responses observed at the first, P1 stage. In the expectancy condition, those relationships become complex, as indicated by the quadratic fit of the dependence of the N1 amplitude on coherence level (Figure 5-6B). Such a nonlinear relationship may be explained by competing tendencies in perception of the motion signals at intermediate levels of coherence. Particularly, random (i.e., 0% coherent) RDKs do not lead to coherent motion representations at all. 100% coherent RDKs may be perceived using only local motion vectors (Cai et al., 2014). But at intermediate levels, perception of dots moving in a single direction among randomly moving dots involves both integration of signal motion and segregation of noise (Husk et al., 2012). This results in higher thresholds for motion discrimination (Habak et al., 2002), which makes these stimulus configurations the most *ambiguous*. High ambiguity may require higher selective attention to separate signal from noise in judgments of coherence, which, however, is necessary only in the expectancy condition. Thus, higher attention may explain the higher N1 amplitude observed at the intermediary levels in the expectancy condition. The N1 has been proposed as an index of a general-purpose discrimination process (Hopf et al., 2002; Vogel & Luck, 2000). Earlier studies have shown that effects of spatial attention on the visual N1 are larger for difficult discriminations than for easy discriminations (Fu et al., 2008; Handy & Mangun, 2000; Parks et al., 2013). In the auditory domain, temporal orientation leads to larger N1 amplitudes for difficult discriminations (Lange & Schnuerch, 2014). Here, we show similar effects for the visual domain.

Modulations of N1 amplitude by grouping difficulty have been described for other types of grouping. Han (2004) investigated grouping by proximity and by similarity when cues for each type of grouping were congruent (easy condition) or incongruent (difficult condition). Larger N1 amplitudes were revealed for grouping by similarity when grouping by proximity was congruent with similarity, compared to when it was incongruent. Villalba-García et al. (2018), studying shape similarity versus proximity grouping, reported a similar N1 modulation by congruence. They suggested that the N1 effect reflects a difference in difficulty ("processing fluency") or visual salience of grouping. This is in line with our interpretation that N1 amplitude reflects a difficulty in discrimination of coherence in RDKs. Crucially, though, difficulty in the case of RDKs does not increase linearly: instead, the RDKs which impose the most difficulty in coherence discrimination are the ones which are neither completely random nor completely coherent.

In sum, we found that expectation is a powerful factor modulating perception of Gestalt global motion and this modulation is most prominent for ambiguous stimulus configurations, which are more difficult to discriminate. These results support the view that perception of motion Gestalts is not purely preattentive (Julesz, 1981; Kahneman & Henik, 1981; Duncan, 1984). Instead, an interesting transition is found between 2 distinct processing stages. Specifically, directing attention through expectancy does not initially (i.e., within the P1 time window) interact with the organization of the stimulus, represented by the coherence level in our study. Afterwards, a switch occurs from the preattentive to attentive stage of Gestalt perception, which in our experiment corresponds to the transition from the P1 to the N1 component, occurring about 160 ms after motion onset. This timing is distinct from that observed for other types of stimuli and Gestalt percepts; for example, for perceptual grouping by similarity and proximity, attention influences on grouping around 100 ms earlier (Han et al., 2005; Nikolaev et al., 2008). The timing of this transition suggests that attention does not deploy "on time" after stimulus presentation but rather only after completion of an initial processing stage. Since coherent motion is processed in the MT area (Rees et al., 2000; Hesselmann et al., 2008; Saproo & Serences, 2014), which is relatively high in visual hierarchy, it is likely that the deployment of selective attention to coherent motion processing also occurs later than in the case of grouping by similarity and proximity, which is associated with V1, V2, and the lateral occipital areas (Altmann et al., 2003). Given that the non-linearity of neural processes increases along the visual hierarchy (Alp et al., 2017), the high level of coherent motion processing may explain the observed non-linear character of its interaction with attention.

An issue left for future investigation is whether effects of expectancy may occur even earlier (i.e., in the C1 time-window). In the current study, we did not investigate this issue because of specific properties of our experimental task. We employed a long task with many (6000) repeated stimulus presentations, which may lead to fast learning and result in modulations of visual ERPs (Ding, 2018). Additionally, the investigation of C1 effects benefits from presentation of stimuli in the upper visual field (Slotnick, 2018), whereas we presented stimuli centrally. Future studies may employ stimuli configured so as to examine the effects of expectancy in C1 and their relationship with Gestalt perception.

A number of psychophysical and ERP studies established different dynamics for different types of groupings. For example, grouping by proximity is achieved earlier than grouping by similarity, which involves more complex processing (Ben-Av & Sagi, 1995; Han, 2004; Kimchi, 2009; Rashal et al., 2017; Villalba-García et al., 2018). Similarly, our results show that common-fate grouping of coherently moving dots has a particular time course that is distinct of other types of grouping. These findings support the current view that perceptual grouping is not a unitary construct and that the operations underlying the various types of grouping have to be studied case by case (Kimchi, 2009; Rashal et al., 2017; Wagemans, 2018).

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Supplementary Materials

Table S5-1

Average number and percentage of epochs accepted and rejected due to artifacts by pre-post expectancy condition.

Condition	N rejected	% rejected	N accepted	% accepted
Expectancy	26	0.80	3274	99
Post-expectancy	26	0.96	2674	99

Table S5-2

Average number and percentage of epochs accepted and rejected due to artifacts by stimulus position.

Stimulus position	N rejected	% rejected	N accepted	% accepted
Position 0	13	2.1	587	98
Position 1	13	2.2	587	98
Position 2	15	2.5	585	98
Position 3	17	2.9	583	97
Position 4	19	3.2	581	97
Position 5	22	3.6	578	96
Position 6	24	3.9	576	96
Position 7	26	4.4	574	96
Position 8	29	4.9	571	95
Position 9	30	5.1	570	95

Table S5-3

Average number and percentage of epochs accepted and rejected due to artifacts by coherence level.

Coherence level	N rejected	% rejected	N accepted	% accepted
0% coherence	18	3.3	526	97
10% coherence	19	3.4	529	97
20% coherence	19	3.4	527	97
30% coherence	18	3.3	527	97
40% coherence	19	3.5	522	97
50% coherence	19	3.5	524	96
60% coherence	19	3.5	530	97
70% coherence	19	3.4	528	97
80% coherence	18	3.3	529	97
90% coherence	19	3.4	531	97
100% coherence	18	3.4	523	97

Table S5-4

Consecutive contrasts between adjacent stimulus positions for the P1, adjusted for multiple comparisons using the Tukey correction.

Condition	Positions contrasted	Estimate	SE	t-ratio	*p*
Post-expectancy	3-2	-0.008	0.110	-0.076	1.000
	4-3	0.258	0.111	2.333	.130
	5-4	0.326	0.111	2.934	**.023**
	6-5	0.130	0.112	1.165	.859
	7-6	0.024	0.112	0.215	1.000
	8-7	0.213	0.113	1.890	.345
	9-8	-0.075	0.111	-0.678	.992
Expectancy	3-2	-0.027	0.108	-0.248	1.000

	4-3	0.139	0.107	1.290	.785
	5-4	0.118	0.107	1.103	.889
	6-5	0.157	0.107	1.463	.662
	7-6	0.009	0.108	0.086	1.000
	8-7	0.154	0.108	1.428	.688
	9-8	0.100	0.108	0.929	.952

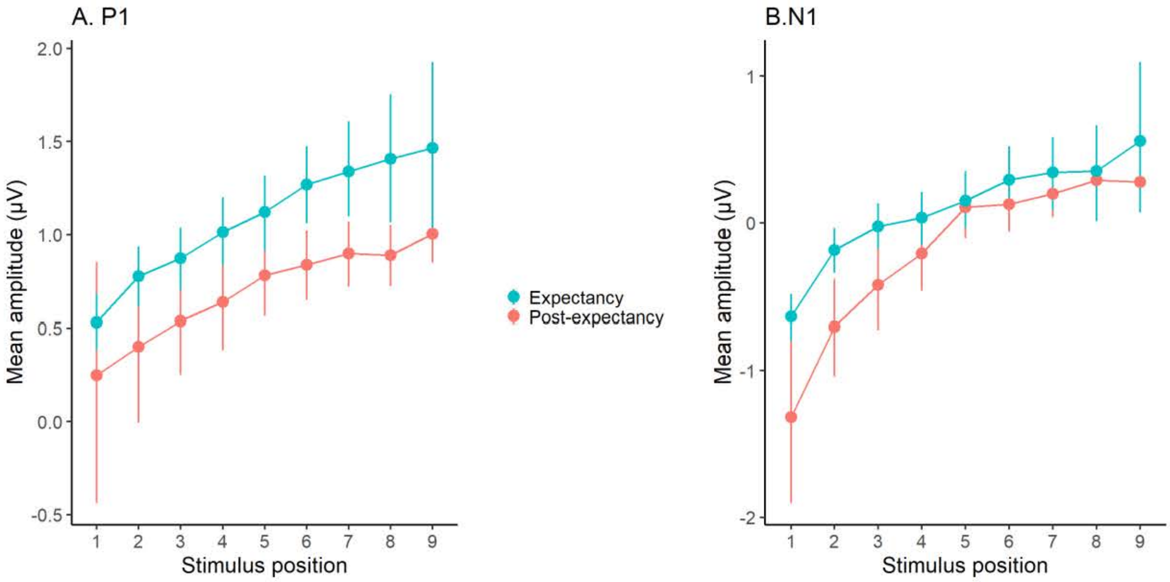
Table S5-5

Consecutive contrasts between adjacent stimulus positions for the N1, adjusted for multiple comparisons using the Tukey correction.

Condition	Positions contrasted	Estimate	SE	t-ratio	*p*
Post-expectancy	3-2	-0.075	0.132	-0.567	.997
	4-3	0.401	0.133	3.022	**.019**
	5-4	0.388	0.134	2.904	**.029**
	6-5	0.049	0.134	0.367	1.000
	7-6	-0.035	0.135	-0.261	1.000
	8-7	0.214	0.135	1.583	.576
	9-8	0.028	0.134	0.208	1.000
Expectancy	3-2	0.023	0.130	0.174	1.000
	4-3	0.034	0.130	0.263	1.000
	5-4	0.215	0.130	1.652	.522
	6-5	0.128	0.130	0.982	.938
	7-6	0.039	0.130	0.301	1.000
	8-7	0.008	0.130	0.065	1.000
	9-8	0.252	0.131	1.926	.330

Figure S5-1

Grand averaged ERP amplitude by stimulus position and in the pre-post cue conditions. A: P1 amplitude. B: N1 amplitude. Data points are means, error bars indicate are standard errors of the means across 27 participants.



CHAPTER 6. GENERAL DISCUSSION

In this thesis, we studied how visual attention influences perceptual organization. We discussed the main theories of attention and their stances on perceptual organization, reviewed studies investigating implicit processing of unexpected stimuli under inattention, and conducted two EEG studies on the occurrence of perceptual organization processes under varying degrees of attention. In this section, we summarize the main findings of the thesis and how they relate to the broader fields of perceptual organization and attention.

Study 1 – Theories of Attention and Perceptual Organization

In Study 1, we briefly reviewed how Gestalt psychology and the main theories of attention in cognitive psychology and cognitive neuroscience view the relationship between attention and perceptual organization in vision. We saw that Gestalt Psychology, in theory, attributed a role for attention in perceptual organization, despite most of the work written by Gestalt psychologists not assigning much importance to attention (Boring, 1929; with exceptions, e.g., Köhler & Adams, 1958). Afterwards, when cognitive psychology was born, early cognitive theories assigned little to no role of attention in Gestalt organization. In constrast, the current picture differs in several aspects, with recent theories challenging the view that perceptual organization is purely preattentive. The empirical literature, drawing from psychological (experimental) and neurophysiological data, shows that top-down attention influences perceptual organization. Moreover, in contrast with earlier theories (e.g., Treisman & Gelade, 1980), the influence of attention in organization is now thought to occur at very early stages of perception. Conversely, Gestalt organization processes, which were previously assumed to be restricted to early stages of the construction of visual percepts (Neisser, 1967; Kahneman & Henik, 1981), are now viewed as occurring at multiple stages of perception and to comprise distinct subprocesses.

Currently, many theories of attention do not distinguish between different Gestalt processes, whereas the mainstream theories on perception that deal with perceptual organization explain only a subset of attentional phenomena. The heterogeneous nature of perceptual organization poses several questions to theories that relate attention and perceptual organization. Those questions include how attention modulates distinct types of perceptual organization processes, such as grouping by distinct factors; how attention resolves competition between distinct subprocesses; and whether the influence of attention varies across perceptual organization phenomena.

In sum, the relationship between attention remains to be explored. The remaining studies on the thesis aimed to contribute to the field using review and empirical methods.

Study 2 – Implicit Processing during Inattentional Blindness

Study 2 reviewed experiments on implicit processing during inattentional blindness in an effort to summarize the conclusions in the field. We concluded that there is considerable evidence that unexpected visual stimuli are processed even when observers are so focused on an attentionally demanding task that they do not notice such stimuli. This includes perceptual grouping of background stimuli, which seems to occur during inattentional blindness. These results tend to agree, at least in part, with the classical view that perceptual organization may occur without attention (Duncan, 1984; Kahneman & Henik, 1981; Treisman & Gelade, 1980). However, some studies also found differences in measures of perceptual organization between participants that noticed and those who did not notice background stimuli, suggesting that attention might not be necessary for perceptual organization, but may modulate it at later stages.

This review also highlighted difficulties with assessing awareness of unexpected stimuli. Measures of awareness vary widely across studies, and within the same study one criterion is chosen from many available to classify participants as aware or unaware (e.g., Razpurker-Apfeld & Pratt, 2008), sometimes without a clear justification. In other cases, it is not clear at all which measure was employed to consider participants as aware (e.g., Rashal et al., 2017). We showed that different criteria lead to distinct rates of awareness across studies, corroborating findings from earlier studies (e.g., Wood & Simons, 2019). Therefore, choosing how to separate participants according to their awareness of the unexpected stimulus (and whether to do that at all, considering the issue of regression to the mean pointed by Shanks, 2017) is a crucial issue to be considered when designing studies on implicit processing during inattentional blindness.

This point calls attention to a broader discussion about the rich vs. sparse nature of conscious perception (Cohen et al., 2016). The choice of awareness measures need to take into account the nature of the unexpected stimulus used in an inattentional blindness study and the possibility that only certain features of that stimulus might be perceived. One of the main arguments for this comes from studies indicating that summary (or ensemble) statistics can often be accessed even when participants are strongly focused on another task (Cohen et al., 2016;

Usher et al., 2018; Ward et al., 2016). Hence, in several inattentional blindness studies, it is possible that participants did perceive the background stimuli, but this may not be detectable if the measures of awareness employed demand access to details of the stimuli.

Despite this caveat, some studies suggest that ensemble perception might be less of an issue for conclusions obtained with inattentional blindness designs (Huang, 2015; Jackson-Nielsen et al., 2017; Mack & Clarke, 2012). Those studies employed measures that were specifically selected to detect perception of summary statistics. They found that ensembles or gist are often *not* consciously perceived when attention to those ensembles is minimized. In particular, one of those studies (Jackson-Nielsen et al., 2017) argues that previous experiments showing conscious perception of ensembles do not limit attention the background stimuli as much as intended. The reason is that those previous experiments used dual-task designs, which had already been criticized decades earlier for not sufficiently limiting attention (Rock et al., 1992), thus leading to partial attention instead of inattention. Jackson-Nielsen et al. (2017) argue that, because coding of ensemble statistics is efficient and requires only minimal attention (Alvarez & Oliva, 2009), the amount of attention available in dual-task designs may be enough to allow for ensembles to be consciously perceived. In contrast, inattentional blindness minimizes attention to the background (although it is questionable if it leads to strict inattention; Most, 2010; Rashal et al., 2017). We conclude that the inattentional blindness studies in our review succeeded in minimizing attention to the unexpected stimuli, reducing the likelihood that summary statistics of those stimuli were consciously perceived. However, the point remains that measures of awareness in inattentional blindness studies need to be carefully chosen, considering the possibility of ensemble perception or other types of less detailed perception.

Study 3 – Implicit Texture Segregation during Inattentional Blindness

In Study 3, we attempted to reproduce earlier results (Pitts et al., 2011) on implicit texture segregation during inattentional blindness using ERPs. However, we succeeded only partially in reproducing the previous results. This discrepancy between our results and those by Pitts et al. (2011) might be due to changes that we made to the design, such as the introduction of an adaptive procedure for the main task, which might have led to a variation in participants' arousal across the blocks.

Alternatively, our results might be explained by the high perceptual load that our main task entailed: to ensure a high rate of inattentionally blind participants, we set a criterion of 50%

performance in our staircase procedure. Such a difficult task might have kept the participants so focused on the main task that minimal attention was left for the background stimuli, eliminating implicit texture segregation. This would mean that texture segregation cannot actually occur in the absence of attention and varies with perceptual load. Although the hypothesis that high perceptual load may have eliminated implicit texture segregation conflicts with a recent study (Pugnaghi et al., 2020), several differences between the type of unexpected stimuli and the implicit measure employed limit the comparison between the results.

This study also shed light on some limitations of inattentional blindness as a tool to investigate of effects of attention on perceptual organization. Because assessment of awareness can only be conducted once before the subject becomes aware of the unexpected stimuli (as a rule; for exceptions, see e.g. Jackson-Nielsen et al., 2017 and Ward & Scholl, 2015, but these are not suitable for general utilization), this assessment has to be conducted either for only one trial or once for whole blocks of trials. In the first case, too few trials are available for analysis (usually only one per participant), increasing the sample size necessary for reliable results in those studies. In the second case, there may be a mixing between trials in which participants notice the unexpected stimulus and trials in which they do not, limiting the type of analysis and conclusions that can be obtained from such datasets, and also allowing for confounds between inattentional blindness and memory issues (Moore, 2001; Wolfe, 1999).

A further complication with inattentional blindness as a tool to study the influence of attention on perception is the limited degree of control over attention which this paradigm allows. Many variables are known which influence rates of inattentional blindness, such as distance from the stimuli of the main task (Mack & Rock, 2000), attentional set (Most et al., 2005), perceptual load (Calvillo & Jackson, 2014; Cartwright-Finch & Lavie, 2007), cognitive (executive) load (Lavie, 2010), number of distractors (Most et al., 2005), and similarity of the unexpected stimulus to the targets (Most et al., 2005; Richards et al., 2012; Simons & Chabris, 1999). However, the main factor involved in the manipulation of attention in inattentional blindness is expectation, which is manipulated by not mentioning the critical stimulus during instruction at the start of the experiment (Braun, 2001; Mack & Rock, 2000; Ward & Scholl, 2015; White & Davies, 2008), increasing the likelihood that the unexpected stimulus is in fact unattended. Because it is hard to control what participants expect in an experiment, and how well they can focus on a task, the proportion of participants who do not notice the unexpected stimulus cannot be determined in advance.

The standard explanation for this variation is that participants who notice the stimulus may not be fully attending to the main task. However, an alternative interpretation is that attention is often necessary for conscious perception, but this is not always the case (Watzl, 2017). Because it is difficult to determine if attention has “spilled” or not to the unexpected stimuli, it is also hard to determine if a group of participants who notice unexpected stimuli are attending or not to a stimulus. Thus, unawareness of a stimulus is assumed to be due to inattention, but participants are assumed not to be attending to a stimulus when they are unaware. The paradigm may not be ideal to study whether attention is necessary for processing of a particular stimulus.

This does not mean that the paradigm is not useful for certain purposes. Besides being a phenomenon with real-world implications (Chabris et al., 2011; Murphy & Greene, 2017; Simons, 2000), when satisfactory measures of awareness are employed, it may reasonably be concluded that participants who do not notice unexpected stimuli are directing very little attention to it (e.g., Jackson-Nielsen et al., 2017). Nonetheless, due to the small degree of control over attention that this paradigm allows, in the next study we decided to employ a task wherein attention could be manipulated in a more controlled manner, manipulating expectations using hazard rates instead of instructions.

Study 4 – Attentional Modulation of Common-Fate Grouping

In Study 4, we explored how temporal expectations (i.e., expectation related to the moment of occurrence of a target) influences perception of motion Gestalts using Random-Dot Kinematograms (RDKs). One of the strengths of this study was the parametric manipulation of the level of motion coherence of the RDKs. This manipulation showed that coherence processing occurred already at 100 ms post-stimulus, as indexed by the amplitude of the P1. This effect followed a linear trend, with P1 amplitude decreasing with coherence. This earlier effect has not been observed in most earlier ERP studies on RDKs, which showed P1 peaks for only some participants (Kavcic et al., 2013; Martin et al., 2010; Zalar et al., 2015).

Temporal expectation had an effect on the processing of the RDKs at that stage, but that effect did not depend on coherence level. We interpreted this as a general readiness for perception which is independent of the stimulus. Contrastingly, in the time window of the N1 wave (starting at 160 ms post-stimulus), we found that attentional modulation varied with the coherence level of the RDKs. This attentional stage of processing seems to be involved in visual discrimination of a stimulus, and thus interacts with its configuration. Although the results for the P1 seem to favor classical views that regard grouping as preattentive (Kahneman & Henik, 1981; Treisman & Gelade, 1980), the later results conflict with such theories. Instead, these results support a view that grouping is a multi-stage, heterogeneous process (Kimchi, 2009; Wagemans et al., 2012), in line with other recent studies (Han et al., 2005; Nikolaev et al., 2008; Villalba-García et al., 2018).

Our finding that temporal expectations influence Gestalt perception adds to other findings of influences of expectation on perception (Nobre & Rohenkohl, 2014; & Van Ede, 2018; Nobre, 2012; Summerfield & de Lange, 2014). Previous ERP studies indicated that temporal attention modulates activity in sensory areas of the cortex under certain conditions (Doherty et al., 2005; Nobre & Rohenkohl, 2014; Rolke et al., 2016). Specifically, ERP studies indicating that expectations by constant foreperiods modulate the amplitude of the posterior visual N1 (Correa et al., 2006; Nobre et al., 2007; Seibold & Rolke, 2014) and N2pc (Seibold & Rolke, 2014), and, less frequently, of the visual P1 (Doherty et al., 2005; Rohenkohl & Nobre, 2011; Zanto et al., 2011). Because the N1 has been proposed to index visual discrimination processes (Luck, 2014), these results suggest that one possible effect of temporal expectations is to enhance the discrimination of visual features.

Importantly, attentional modulation was larger for stimuli with intermediary coherence levels, which were also the most ambiguous ones. A related finding comes from a study investigating attention to features (Snyder & Foxe, 2010). They manipulated feature-based attention with probabilistic cues in an analogous manner to the Posner spatial cueing paradigm (Posner et al., 1980). Strength of common-fate grouping was manipulated by changing whether all dots in an RDK moved in the same or different speeds. When grouping was strong, they found weaker facilitatory effects by valid cues compared to when grouping was weak. Assuming that attentional direction to features by endogenous cues involves suppression of the irrelevant feature they concluded that this difference indicated that strong grouping counteracted such suppression by leading to automatic spread of attention along the (object) stimulus.

A follow-up study (Snyder et al., 2012) showed that, when attention was directed to relevant features, presentation of weak Gestalt groupings showed ERPs related to attention (as a consequence of cueing) peaking at 180 ms, but not to strong groupings. They concluded that feature-based attention is attenuated by common-fate grouping. Considering the time window analyzed, such attenuation should occur at some point before 180 ms, indicating a competition between top-down feature-based attention and bottom-up grouping. Additionally, they suggest that feature-based attention precedes grouping, which leads to an object-based spread of attention.

Such an account might explain our results. It is possible that a first stage of common-fate grouping consists of the activation of directional selective neurons, which is followed by an inhibition mechanism that suppresses incompatible directions. Indeed, our participants reported that estimating the coherence of RDKs with intermediary coherence levels felt more difficult, which might reflect the need for this attentional suppression process. This is coherent with the account of common-fate grouping by Levinthal and Franconeri (2011), in which common fate grouping is analogous to similarity grouping, which itself occurs later in time than grouping by proximity, and is attentionally demanding.

The study by Snyder et al. (2012) added support to the proposal (e.g., Roelfsema, 2006) that grouping and feature-based attention share physiological mechanisms. The authors suggest that those common mechanisms might be alpha-band oscillations, which are associated with sensory suppression (Foxe & Snyder, 2011; Van Diepen et al., 2019). The role of alpha activity has been observed before in the context of object coherence, when higher alpha power was observed for non-objects than for objects, but only when a discrimination was necessary (Vanni et al., 1997). Snyder et al. (2012) hypothesized that grouping leads to a spread of feature-based attention over an object’s constituent features. Those results can also be interpreted according to the biased competition hypothesis, given analogous results from earlier studies (McMains & Kastner, 2011) showing larger effects of spatial attention for weak groups than for strong groups.

We hypothesize that alpha activity might be similarly involved in the modulation of grouping by temporal expectancies. It has been observed for several years that alpha oscillations can be entrained to external stimuli and have a role in temporal expectancies (Mathewson et al., 2009, 2012; Van Diepen et al., 2019). Such entrainment results in the synchronization of attentional pulses to the stimuli (Large & Jones, 1999), similarly to what has been suggested to underlie the attentional awakening phenomenon (Ambinder & Lleras, 2009). Such synchronization may support perceptual effects of temporal attention (Mathewson et al., 2012;

Schroeder & Lakatos, 2009) through the modulation of processing of irrelevant elements in a grouping pattern by alpha oscillations. In this study, we only used ERPs as a measure of attentional allocation. Given that brain oscillations have been pointed as mechanisms that support perceptual organization (van Leeuwen, 2015), it is important to investigate how the dynamics of oscillations in temporal expectations influences Gestalt phenomena.

Concluding Remarks

The relationship between the concepts of attention and Gestalt organization is a complex one. Attention and perceptual organization do not have common scientific roots. Attention was once deemed of fundamental importance in introspectionist psychology (Kahneman, 1973), to the point where Titchener (1908) claimed that the "doctrine of attention" was one of the foundations of psychology. However, that tradition of psychology was also associationist (Hamlyn, 1957). When Gestalt psychology was developed, rejecting associationism (Wagemans et al., 2012), perceptual organization entered the spotlight, but it also moved attention aside (Boring, 1929; Kahneman, 1973). Even if the phenomenological philosophy which inspired Gestalt psychology did discuss the nature of attention (Vermersch, 2004) – in part influenced by William James (Yoshimi & Vinson, 2015) – the Gestalt psychologists themselves did not systematically investigate attention in their experimental and theoretical work (Boring, 1929).

It might be the case that Gestalt theory simply has no need for a concept of attention (van Leeuwen et al., 2011). But the diminished importance of attention in Gestalt psychology might have rather been motivated by the manner in which the concept of attention was used at the time when Gestalt psychology was born. Back then (as sometimes also today; Anderson, 2011; Hommel et al., 2019), attention was often used as an ad hoc explanation for unexpected phenomena or experimental results (Bradley, 1886; Koffka, 1935). However, Cognitive Psychology restored the concept of attention to incorporate mechanisms internal to the organism in the explanation of psychological phenomena (Kahneman, 1973), and motivated research that described a large number of important phenomena which need to be integrated with a proper explanation of perceptual organization phenomena.

Despite the conceptual confusion surrounding the concept of attention (Allport, 1993, 2011; Anderson, 2011; Di Lollo, 2018; Hommel et al., 2019), considerable progress has been made empirically in the study of attentional phenomena (Nobre & Kastner, 2014). We adopt the view that the concept of attention refers to a real first-person phenomenon (Watzl, 2017) that cannot be ignored; in a way, “Everyone knows what attention is” (James, 1918). However, as a scientific object of study, attention needs much investigation, both theoretically and empirically. We believe that relating attention to the phenomena uncovered by Gestalt Psychology may contribute to advancing the understanding of this construct.

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APPENDICES

APPENDIX A

AWARENESS QUESTIONNAIRE FOR STUDY 3

Post-phase questionnaire

Phase:_____ Subject:______

Date:____________

1) During this session, did you notice any patterns within the little white lines in the background?

☐ Yes	☐ No

2) If you did notice any patterns, at which moment during this session did that first happen?

- ☐ During blocks 1 to 3
- ☐ During blocks 4 to 7
- ☐ During blocks 8 to 10

3) If you did see any patterns, please describe (or draw) what you saw in as much detail as possible.

* For the items below, the experimenter will provide examples on the computer screen.

4) Rate how confident you are that you saw each pattern during the experiment.

Please use the following scale:
1 – very confident I did *not* see it
2 – confident I did *not* see it
3 – uncertain
4 – confident I saw it
5 – very confident I saw it

Diamond	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Horizontal rectangle	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
X pattern	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
One big square	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Four small squares	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Vertical rectangle	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5

5) Estimate how often you saw each pattern during the experiment.

Please use the following scale:
1 – never
2 – rarely/less than 10 times
3 – infrequently/10-50 times
4 – frequently/50-100 times
5 – very frequently/more than 100 times

Diamond	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Horizontal rectangle	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
X pattern	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
One big square	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Four small squares	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Vertical rectangle	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5