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INDIVIDUAL DIFFERENCES IN CHANGE BLINDNESS

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For my family, my friends, and
My colleagues
Who became my friends as well.

List of scientific publications of the publication-based dissertation

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Manuscript 1

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„We don´t see things as they are, we see them as we are."

Anais Nin

1 Introduction – Individual differences in change blindness

"Driver misses stop sign, hits police car" (Parks, 2015) - such a headline appears in the news nearly every day: A car driver does not notice a motor cyclist ("Übersehen!," 2015) or a bicyclist ("Autofahrer übersieht," 2015). A pilot overlooks another airplane (Schnitzler, 2010), a high-voltage line (Engelberg, 2014), or even a ferris wheel ("Pilot übersieht Riesenrad," 2011). As demonstrated by these unfortunate incidents, failures of human perception happen frequently. *Change blindness* refers to the phenomenon that sometimes observers do not notice changes in the visual environment when they co-occur with some other visual disturbances (Simons & Levin, 1997). For example, drivers might be distracted by *mudsplashes* on the windscreen and, hence, miss the sudden appearance of an overtaking vehicle, resulting in a car crash (cf. O'Regan, Rensink, & Clark, 1999; Simons, Franconeri, & Reimer, 2000).

The history of research on change blindness dates back to the 19th century. In his book *Principles of Psychology*, W. James (1890/1950) refers to the inability to detect changes and discusses the conditions under which objects are discriminated from each other in human perception. Training and personal interest may be identical in their effect as large perceptual differences. In the further historical course, research on change blindness can be divided into three different periods (Rensink, 2002). In the first phase, initial scientific interest developed in the 1950s and 1960s with works, e.g. by French (1953), Ditchburn (1955), Kahneman (1968), or Shepard (1967). Change blindness was typically induced by a temporal gap or a saccadic eye movement. For example, French (1953) showed that increasing the number of dots and the spatial distance between them leads to a reduced discrimination of abstract dot patterns. Together, these studies were the first to empirically demonstrate that observers have great difficulties in detecting changes. The scientific observations of the first phase, however, were not integrated into a general explanation of change blindness (cf. Rensink, 2002).

In the second phase, research on change detection was extended (cf. Rensink, 2002). In the 1970s and 1980s, it was shown that observers are blind to changes under a variety of different experimental conditions, e.g. they did not detect changes of letters (e.g., McConkie & Zola, 1979; Pashler, 1988) or of abstract patterns through dots, circles, or lines (e.g., Bridgeman, Hendry, & Stark, 1975; Phillips & Singer, 1974). These studies paved the way for a theory on visual short-term memory that is limited in its capacity. However, this theory could not be integrated, however, into a basic rationale about change blindness (cf. Rensink, 2002).

Finally, in the third and still ongoing phase, research on change blindness was expanded to a variety of paradigms (cf. Rensink, 2002). For example, in real life experiments, even major changes, such as the exchange of a whole person, were not detected by a great number of participants (e.g., Levin, Simons, Angelone, & Chabris, 2002; Simons & Levin, 1998). In a laboratory setting, a variety of experiments investigated how changes of abstract patterns (e.g., Rensink, 2000b), of photographs (Simons, 1996), or in short films (e.g., Levin & Simons, 1997) were detected or went unnoticed. In contrast to the first and the second phase of the research on change detection, an attempt was made to find a universal framework for explaining the causes of change blindness (e.g., Rensink, 2002; Simons & Levin, 1997; Simons, 2000; Simons & Rensink, 2005). It was stressed that change blindness is an important phenomenon which may help to understand attention and consciousness in visual perception (cf. Simons & Ambinder, 2005). Most researchers agree that *visual selective attention* is a process which is necessary for successful change detection (e.g., Eimer & Mazza, 2005; Rensink, O'Regan, & Clark, 1997). Moreover, also *post-perceptual processes*, i.e. a later stage of the conscious evaluation of a change for ongoing action planning and decision making, are fundamental for the aware detection of changes (Koivisto & Revonsuo, 2003; Rensink, 2000a).

Recently, researchers have begun investigating individual differences in change blindness (cf. Simons & Ambinder, 2005), such as in age (e.g., Costello, Madden, Mitroff, & Whiting, 2010), in cultural differences (e.g., Masuda & Nisbett, 2006), or in expertise (Werner & Thies, 2000). For example, football experts detected more changes in domain-related, semantic photographs of action scenes and scenes of playing formations than novices (Werner & Thies, 2000). Together, these studies confirmed the existence of individual differences in change blindness, assessed by a variety of different paradigms. Nevertheless, these differences have not yet been analyzed sufficiently (cf. Rensink, 2002; Simons & Ambinder, 2005). Two main questions concerning individual differences in change blindness remain. First: Do systematic individual differences in change blindness exist? It remains unclear whether change blindness is a *trait*, i.e. a variable that is consistent across time, different situations, and different methods (McCrae & Costa, 2003; Steyer, Ferring, & Schmitt, 1992). This question has a high practical implication. Individual differences in change blindness may be related to performance in real life task that demanding the detection of changes in a variety of circumstances, e.g. in navigation, surveillance, or driving (cf. O'Regan et al., 1999; Simons & Levin, 1998). In regard to driving, e.g., it is important to know for the prevention of car accidents why some people do not notice changes on the road, whereas others detect them more readily. Second: How can individual differences in change blindness be explained? It remains disputable which underlying cognitive processes contribute to the explanation of individual differences in change blindness. Both, attentional processes and post-perceptual processes may explain these differences.

The present work is structured as follows: First, the phenomenon of change blindness and its underlying processes are introduced in detail. Second, the work focuses on individual differences in change blindness and the current research issues are clarified. Third, I will introduce its methodological procedure, adapted for the research of individual differences in change blindness. Fourth, the results of these research questions are reported and discussed in two main chapters: a) cognitive processes of change blindness and b) individual differences in change blindness. Fifth, the present findings about individual differences in change blindness are applied to the example of cognitive aging. Finally, a general discussion summarizes all observations.

2 Change blindness

In a visually rich environment we do not perceive all the details of objects or scenes from one view to the next (e.g., Henderson, 1997; Rensink, 2000b). Consequently, it may happen that observers miss changes in a visual scene when they occur simultaneously with some other visual disturbances. This phenomenon is known as change blindness (e.g., Simons & Levin, 1997). In a typical change blindness experiment, an original image is presented in rapid succession with a slightly modified image. This change usually produces a transient motion signal attracting the observers' attention automatically. The motion signal of the change can be completely masked, e.g. by saccadic eye movements (e.g., Grimes, 1996), by a blank (Rensink et al., 1997), by the occlusion of the change (e.g., Simons & Levin, 1998), by shifts of the entire display (e.g., Blackmore, Brelstaff, Nelson, & Trościanko, 1995), or by film cuts (e.g., Levin & Simons, 1997). As a consequence, observers often have difficulties to integrate visual information from one view to the next and to detect changed visual information. Change blindness may also occur when the change is not presented during a gap, a saccade, or a shift. For example, gradually changing stimuli often go unnoticed (e.g., Simons et al., 2000). Furthermore, changes may be missed when irrelevant stimuli, like mudsplashes that are presented simultaneously with the change, reduce the *salience*, i.e. the way how a stimulus is outstanding relative to other stimuli, of the motion signal of the change (e.g., Schankin & Wascher, 2007, 2008; O'Regan et al., 1999).

First of all, the term *change* should be defined precisely. Change "refers to the transformation over time of a single structure" (Rensink, 2002, p. 250). Change can be differentiated from *difference* and *motion* (Simons & Rensink, 2005; Rensink, 2002). Difference is described as a poor resemblance between two structures that may also occur at the same time (Rensink, 2002). Consequently, both change and difference refer to a comparison of similarities between structures. A motion of a quantity usually appears continuously in real-life and can be characterized by the relocation of an object (Rensink, 2002). More precisely, change may come with a motion or it may appear suddenly. These often related terms, however, can be separated experimentally (Rensink, 2002).

Moreover, change blindness has to be differentiated from similar phenomena, which also focus on the role of capacity limited systems, that are crucial for the perception and processing of stimuli in the environment (cf. Rensink, 2002): *repetition blindness* (e.g., Bavelier, 1994; Kanwisher, 1987), the *attentional blink* (e.g., Raymond, Shapiro, & Arnell, 1992; Shapiro, Raymond, & Arnell, 1997), and *inattentional blindness* (e.g., Mack & Rock, 1998; Simons & Chabris, 1999). Repetition blindness describes the struggle of observers to detect the second one of two identical targets that are presented in rapid and repeated sequence (Rapid Serial Visual Presentation (RSVP); Chun, 1997; Kanwisher, 1987). Repetition blindness occurs because observers are not able to perceive two targets as episodically different (Dux & Marois, 2009). In contrast, change blindness also appears when changes are not presented in rapid and repeated sequence. The attentional blink phenomenon includes a temporary attentional lapse due to the inhibition of a second changed target (Dux & Marois, 2009; Shapiro et al., 1997). In particular, when two distinct target items are shown successively, separated by about 500 ms, observers often cannot identify the second target, although they do not have any problems when it is presented alone. Change blindness, however, also appears when changes are shown after this critical psychological refractory period of attention. In a typical inattentional blindness paradigm, participants perform a task while simultaneously and without their knowledge an irrelevant, but clearly visible object is presented in their visual field (Simons & Chabris, 1999). A majority of observers does not notice the existence of this critical, but unexpected object (Simons & Chabris, 1999). In contrast to this *incidental* task, change blindness tasks have been labelled *intentional* (Simons, 2000): That is, change blindness does not investigate if the existence of an object has been noticed, but observers actively search for a change which has been announced before.

3 Explanations for change blindness

The question remains, why changes are often missed. There are five possible explanations for change blindness (Simons, 2000): First, the original representation, i.e. the encoding of the visual details of a scene, might be *overwritten* or substituted by the changed representation. Second, only the *first impression* of the original scene is represented, whereas an encoding of the changed scene fails. Third, the visual environment can be seen as a memory store and visual information is only abstractly encoded by the observer. Neither the original scene, nor the modified scene is represented and *nothing is stored*. Fourth, a missing comparison process between the initial and the modified scene might cause change blindness, because *nothing is compared*. Fifth, the features of the original scene and the modified scene are combined in an erroneous *feature combination*. Thus, change blindness is prevented when the comparison process of both the correctly represented original scene and of the changed scene is successful (Simons, 2000; Simons & Rensink, 2005).

But which specific cognitive processes are responsible for a correct encoding of both scenes, i.e. the original scene and the changed scene, and a successful comparison process so that changes are detected? According to Rensink (2000a), who gave a theoretical overview about the processing of stimuli, change detection can be separated into three different *aspects of vision*: First, *seeing* a change includes its representation in visual perception. As the outside world is not stably represented in detail, seeing is a dynamic process making a holistic structure available when necessary. Second, *sensing* of a change was defined as the nonattentional processing of visual information without conscious awareness (Rensink, 2000a). For example, in a study about the unconscious processing of visual changes, participants were asked to detect a positional or identity change of letters and number, which served as stimuli (Niedeggen, Wichmann, & Stoerig, 2001). Observers sensed the presence of a change before they could consciously detect or identify it. Third, focused visual attention is necessary for post-perceptual processes, such as *scrutinizing* the change. The emphasis of the present work is on attentional processes and on post-perceptual processes in change detection.

Since the 17th century humans have been taking interest in the phenomenon of attention (Mole, 2013). According to the Enlightenment philosopher René Descartes, attention that is described as a "surprise of the soul", is allocated to "rare and extraordinary" objects (Descartes, 1649/1996, p. 109). In the 18th century, the definition of attention as "state of mind which prepares one to receive impressions" by Kames (1796/2005) reveals that it was conceived to control cognitive, perceptual input. Also in contemporary definitions, this *selectional* function was defined as one important aspect of attention (e.g., Goldhammer, 2006; Posner & Boies, 1971; Desimone & Duncan, 1995): Selected stimuli are preferably processed in comparison to irrelevant stimuli, because selective or focused attention is characterized by a limited processing capacity (e.g., Broadbent, 1958; Posner & Boies, 1971). With reference to this, one of the most important, theoretical approaches was made by Broadbent (1958), fundamental for ongoing research (cf. Mole, 2013; H.J. Müller & Krummenacher, 2008). It was suggested that perception worked like a selective two-serial-system, limited to one channel and in also in its capacity, similar to a bottleneck. Attention controls this bottleneck by determining the connection and the passing of the stimuli from a large capacity, pre-bottleneck system, which exclusively selects stimuli due to simple physical characteristics, to a reduced capacity, post-bottleneck system. Following empirical findings, however, that showed that also not attended information can be processed were not compatible with this theory (e.g., Moray, 1959; Treisman, 1964). Together, in an older standard view, attention was regarded as serial, high-speed mental *spotlight* scanning the visual field (e.g., Posner, Snyder, & Davidson, 1980).

Findings from visual search studies were fundamental for further conclusions about selective attention (e.g., Jonides & Yantis, 1988; W. Schneider & Shiffrin, 1977; Treisman, 1982). In a typical visual search paradigm, participants are asked to detect a target, e.g. a blue letter, usually presented among task-irrelevant, distracting stimuli, e.g. red and green letters (e.g., Treisman, 1982). Visual search studies have shown that the competition in selective attention is biased by automatic, stimulus-driven *bottom-up* mechanisms (e.g., Jonides & Yantis, 1988) and goal-driven *top-down* mechanisms (e.g., W. Schneider & Shiffrin, 1977). Via bottom-up mechanisms, stimuli are separated from their background. The observers' attention is automatically attracted by perceptually salient stimuli in a homogeneous array of distractors in a fast and exogenous way. In contrast, top-down mechanisms guide observers' attention in a deliberate and controlled manner toward information that is relevant for their individual goals. Based on these findings, the standard view on attention as a mental spotlight was fundamentally doubted in an innovative review that integrated these behavioural and further neuropsychological findings into *biased competition theory* (Desimone & Duncan, 1995). This theory states that visual selective attention may not be regarded as a mental spotlight, but as an *emergent property* which is influenced by parallel interactions, such as bottom-up and top-down mechanisms, in a competitive way. Stimuli compete for limited cognitive processing capacities and for the control of behaviour.

In the context of change detection, it has been broadly suggested that focused attention is one major process which underlies successful change detection (e.g., Beck, Rees, Frith, & Lavie, 2001; Eimer & Mazza, 2005; Rensink et al., 1997; Simons, 2000). That is, only changes in the focus of selective attention can be reported consciously, as attention is necessary for an aware representation of a change (e.g., O'Regan, Deubel, Clark, & Rensink, 2000; Rensink et al., 1997). This role of selective attention in change detection is also supported by neuroimaging studies. They indicate that both dorsal frontoparietal regions and extrastriate ventral visual areas are involved in conscious change detection (e.g., Beck et al., 2001; Huettel, Güzeldere, & McCarthy, 2001). Former ones are involved in selective attention (e.g., Coull, Frith, Frackowiak, & Grasby, 1996). Both stimulus-driven bottom-up mechanisms and goal-driven top-down mechanisms affect the allocation of attention in change detection. For example, when the presentation time of the blank was enhanced, change detection performance decreased (Phillips & Singer, 1974), most likely because the salience of the motion signal became smaller (bottom-up). Furthermore, varying the way how observers search for a change had an effect on change blindness (top-down). For example, Rensink et al. (1997) investigated how a manipulation of the interestingness of an object in a visual scene affected change detection performance. Interestingness had been rated before in an independent experiment. The observers were presented changes of objects either with marginal interest or with central interest. Participants had great difficulties in detecting changes of marginal objects in comparison to central objects. Similarly, Lamme (2003) showed that change detection performance was greatly improved when the position of possible changes were indicated by a preceding cue. However, when participants had no information about the potential occurrence of changes, they remained completely change blind (Schankin & Wascher, 2008). Thus, change detection was only possible when some additional knowledge was provided to the observers. To conclude, attention, which can only be allocated to a few items at a time (e.g., Rensink, 2000b; Cowan, 2000), is the key process for successful change detection.

Post-perceptual processes are a later phase of conscious stimulus evaluation (cf. Koivisto & Revonsuo, 2003). They are influenced, e.g., by working memory mechanisms, which temporally store and process information for ongoing more complex cognitive operations, e.g. reasoning (Baddeley, 1992). Incoming stimuli have to be evaluated with regard to previous representations in working memory. This actualization of the mental representation through new information is called working memory updating (cf. Ecker, Lewandowsky, Oberauer, & Chee, 2010; Morris & Jones, 1990; Yntema & Mueser, 1962). In driving, e.g., a conscious visual representation of the oncoming traffic is persistently updated by every look in to the side mirror (Gugerty, 1997). Working memory updating may or may not involve the need to retrieve the initial information, the transformation of old information through new representations, or the complete substitution of old information (Ecker et al., 2010). Post-perceptual evaluative processes are also important for ongoing decision making and action planning (Koivisto & Revonsuo, 2003; Rensink, 2000a). In abstract terms, a decision can be defined as a goal-oriented process which “weighs priors, evidence, and value to generate a commitment to a categorical proposition intended” (Gold & Shadlen, 2007, p. 536). Decision making is based on a variety of sources of information: *Prior* is the probability for a true hypothesis based on the prevalence of previous occurrences, e.g. the frequency of the presentation of a stimulus before specific *evidence* can be accumulated about it. *Values* affect the decision making process by weighing it in one or the other direction by subjective costs or benefits. A decision variable aggregates these different sources of information. Eventually, a decision is made when sufficient sensory evidence is accumulated and, as time passes by, the boundary of a certain criterion is crossed (O'Connell, Dockree, & Kelly, 2012). In this case, perceptual experience has reached access consciousness, i.e. it is reportable and applicable for reasoning and action planning (Block, 1995, 1996). Finally, a decision may be transformed into an action, e.g. in an explicit answer to a question or the pressing of a response button. Theoretically, a change in any or all of these post-perceptual processes may also affect change detection performance. However, there is less research about post-perceptual change processing than about attentional change processing. It has been suggested that post-perceptual evaluative perceptual processes may also play an important role in change detection performance (Eimer & Mazza, 2005; Koivisto & Revonsuo, 2003; Rensink, 2000a; Rensink et al., 1997). For the decision whether or not a change has occurred, the original image and the altered image have to be encoded and compared, then the comparison of these two images has to be consciously evaluated as a change (Block, 1995, 1996; Eimer & Mazza, 2005; Simons, 2000). Working memory updating may affect this evaluation process. For example, it was concluded that only when visual memory updating exceeds a certain threshold, a change can be reported consciously (Hollingworth & Henderson, 2004). This interpretation is in accordance with other research pointing out that only when a certain criterion is crossed, a threshold-bound decision whether a change has occurred or not is made (O'Connell et al., 2012).

4 Electrophysiological correlates

Measuring the brain activity helps to gain further insight into the underlying processes in change detection and change blindness (cf. Beck et al., 2001). Event-related potentials (ERPs) allow a high temporal resolution for a fine-grained analysis of neurocognitive processing. The emphasis of the present work is, firstly, on the N2pc, an ERP waveform reflecting the spatial allocation of selective attention (e.g., Eimer, 1996). Second, post-perceptual processes are reflected by the P300 or P3 component (e.g., Verleger, Jaśkowski, & Wascher, 2005).

The N2pc is one component in the ERP which reflects observers’ allocation of visual selective attention (e.g., Eimer, 1996). It is extracted from the ERP by subtracting the activity ipsilateral from those contralateral relative to the position of a change about 200 to 300 ms after stimulus onset. The N2pc indicates that observers’ have directed their selective attention to a particular location in space (Eimer, 1996; Luck & Hillyard, 1994a, 1994b). Initially investigated in visual search studies, it was suggested to reflect the selective processing or attentional filtering of target stimuli (e.g., Eimer, 1996; Luck & Hillyard, 1994a, 1994b; Woodman & Luck, 1999, 2003). For example, Eimer (1996) investigated the conditions under which an N2pc component is observable. A lateral target stimulus was presented among a varied number of distractors in a visual search task. An N2pc was elicited by the target in three different conditions: when the target (a letter) differed in its form with respect to the distractors (line patterns), when the target (blue or green) was distinguishable with regard to color from the irrelevant stimuli (yellow), and even when the target (a position word, e.g. left) differed in its semantic meaning from the distractors (a color word, e.g. white). The N2pc also mirrors effects of bottom-up and top-down mechanisms on the allocation of attention (e.g., Zhao et al., 2011; Mazza, Turatto, & Caramazza, 2009). Bottom-up influences mainly become visible in the latency and/or the amplitude of the N2pc component (e.g., Mazza et al., 2009), whereas top-down mechanisms are reflected by the N2pc amplitude only (Eimer & Kiss, 2008, 2010; Kiss & Eimer, 2011).

The attentional processing of targets in visual search is very similar to attentional change processing (Busch, Fründ, & Herrmann, 2010). For example, in the context of change detection, the N2pc component was analyzed while participants had to detect and subsequently to identify changing objects, e.g. an umbrella or a watering can (Busch, Fründ, et al., 2010). An N2pc was only elicited when the identity of the objects could be correctly reported, whereas it was absent when changes remained completely unnoticed. This observation is in line with the majority of studies that found an N2pc for stimuli reaching visual awareness, e.g. when participants reported changes of facial expressions (Eimer & Mazza, 2005), of simple bars (D. Schneider, Beste, & Wascher, 2012), or of colored dots (Schankin & Wascher, 2007). Few researchers have shown that an N2pc of a smaller amplitude may also occur in undetected changes (Schankin & Wascher, 2007, 2008; Schankin, Hagemann, & Wascher, 2009), whereas others could not replicate this finding (e.g., Busch, Dürschmid, & Herrmann, 2010; Eimer & Mazza, 2005). It was suggested that the N2pc can be seen as an indicator of an attentional process that is necessary for awareness (Schankin & Wascher, 2008; Schankin et al., 2009).

Effects of post-perceptual stimulus processing are reflected by relatively late ERP components. The P3 is a peaking positivity about 300 ms after stimulus onset with a large amplitude. It was first described by Sutton, Braren, Zubin, and John (1965) as reaction to an unexpected task-relevant event. A distinction can be made between two subcomponents of the P3: the novelty P3 and the classical P3b (e.g., Comerchero & Polich, 1999; Courchesne, Hillyard, & Galambos, 1975; Polich, 2007). The novelty P3, which is maximal at frontal/central electrodes, reflects the attention-driven evaluation of new stimuli and is typically elicited when new stimuli, e.g. deviant letters, are presented among standard stimuli (e.g., D. Friedman, Cycowicz, & Gaeta, 2001). In contrast, the P3b, which has a maximal amplitude at parietal and central midline scalp sites, is enhanced for deviant stimuli, actively searched for by the observer (e.g., Polich, 2007). This component, which is in the focus of the present work, will be referred to as P3. The oddball-paradigm, i.e. when an infrequent target stimulus is presented among a sequence of other irrelevant stimuli, is a typical P3 eliciting paradigm (cf. Polich, 2003). Moreover, the P3 is also evoked by a variety of different tasks (cf. Kok, 2001), e.g., by single-stimulus paradigms (e.g., Polich & Heine, 1996), by recognition tasks (e.g., Courchesne, Courchesne, & Hillyard, 1978), or by complex perceptual operations (e.g., Ullsperger, Metz, & Gille, 1988). The P3 has most commonly been interpreted as reflecting context or working memory updating (e.g., Donchin & Coles, 1988; Verleger, 1988). Moreover, its amplitude size is influenced by the meaning of the eliciting stimulus, i.e. by the emotional value, by task difficulty, or by interacting effects of stimulus probability and task relevance (Kok, 2001). More recently, it has been stated that it reflects a memory process, elicited by stimulus evaluation, necessary for a behavioral response, which helps to transform a decision into action (Kok, 2001; Verleger et al., 2005).

In the context of change blindness, a greater P3 amplitude reflects successful change detection, as indicated by a variety of studies (Koivisto & Revonsuo, 2003; L. Li, Gratton, Fabiani, & Knight, 2013; Niedeggen, Wichmann, & Stoerig, 2001; Polich, 2007; Turatto, Angrillia, Mazza, & Driver, 2002). For example, when participants had to detect visual changes to letters either in identity or in position, the detection of a change was accompanied by an enhanced positivity in the P3 latency range, whereas for undetected or no changes no such effect was recorded (Niedeggen et al., 2001). This *change blindness effect* on the P3 amplitude was also replicated in similar research (e.g., Koivisto & Revonsuo, 2003). It was concluded that the P3 component mirrors late processes of change evaluation, necessary for ongoing decision making and action planning, e.g., of the communication of the detected change (cf. Koivisto & Revonsuo, 2003). In accordance with this, O'Connell et al. (2012) investigated the role of the P3 component and the formation of decisions via accumulated perceptual evidence. Participants were asked to detect gradual reductions in contrast of a continuously presented flickering annulus. ERP analyses showed a single, centro-parietal positivity which grew in amplitude with accumulating sensory evidence and peaked simultaneously when participants responded. The amplitude of this positivity increased with higher change detection probability. The authors concluded that the positivity, which can be equalized with the P3 component, mirrors a goal-oriented decision making process, determined by threshold-bound accumulation of perceptual evidence.

You have your way. I have my way. As for the right way,
the correct way, and the only way, it does not exist.

Friedrich Nietzsche

5 Individual differences

What makes a person individual? Individuality can be described as “the particular character or aggregate of qualities that distinguishes one person or thing from others” (Individuality, n.d.). Within a scientific context, McAdams (1995) provided a theoretical framework for an exhaustive overview of individual differences. He suggested that individual differences are based on three different, but loosely related levels that help to define individuality of a person. The first level includes *traits* hinting at a dispositional portion of individual differences. The second level covers *personal concerns*, e.g., personal values and motivational goals, defense, or coping strategies, specific abilities in a certain domain, missions in life, or values that have to be related to the time in which the person lives and his or her cultural background. Level one (traits) and two (personal concerns) can be generalized to all societies. In contrast, level three describes the individuality and the history of a person, mainly relevant for adulthood and almost exclusively characteristic of Western adults. In sum, identity is considered as unique, purposeful, and meaningful, based on a *life story* which integrates the past, present, and anticipated future.

No description of a person is complete without describing the trait level (McAdams, 1995). Allport (1937/1961) established the concept trait in psychology. He stressed that a trait is characterized by a high generalizability and consistency of behaviour and marked by biophysical evidence. Allport’s idiographic view, which focused on the uniqueness of a person, was fundamental for still ongoing research on traits. Later approaches dropped the somatic basis and emphasized the importance of stability for the description of abstract traits (cf. Hagemann & Meyerhoff, 2008). It was stressed that traits include linear, dimensional constructs, detached from conditions or context (McAdams, 1995). Consistent traits differ systematically across persons and have to be differentiated from *states* that are intraindividually unstable over time, e.g. different levels of fatigue or stress (Cattell, 1973). States and traits do not describe two different categories, but opposed poles of one dimension (Cattell, 1973). Current approaches agree that a trait can be defined as a variable that is stable across time, across different situations, i.e. different states, and across distinct methods (e.g., McAdams, 1994, 1995; McCrae & Costa, 2003; Steyer et al., 1992).

An attribute can be characterized as a trait when the decomposition of its variance relies to a greater portion on differences between persons than between situations (Cattell, 1973). Structural equation modeling has formalized this consideration (e.g., Hoyle, 1995). To improve the understanding of state-trait measurements in psychological measurement, research on structural equation modeling was extended to longitudinal data (cf. Hertzog & Nesselroade, 1987). In particular, by applying the latent state-trait (LST) theory, it is possible to separate effects of the person, of the situation, and of the interaction between the person and the situation (Hagemann & Meyerhoff, 2008; Steyer, Schmitt, & Eid, 1999). Following classical test theory, the core of LST models is based on two main variance decompositions: First, the variances of the manifest variables can be decomposed into the variances of the latent states and of the measurement errors. And second, the variances of the latent state components can be decomposed into the variances of the latent state residuals and of a latent trait. Several repeated measurements are necessary for the separation of trait effects from situational effects. Furthermore, so-called latent method factors, which describe the influence of different methods, can be integrated into the model. Finally, it is possible to evaluate the influence of the trait, of the state, of the method, and of the measurement errors through standard LST indices (cf. Deinzer et al., 1995; Steyer et al., 1992). Together, LST theory has the advantage that it allows for the description of the latent variables without measurement errors or other unwanted influences (cf. Bollen, 1989).

What do we know about individual differences in change blindness? Past research indicates that a majority of persons does not detect visual changes when those co-occur with some other visual disturbances, whereas other persons are not change blind (cf. O'Regan et al., 1999; Simons & Levin, 1998). It is known that observers extremely overrate their change detection performance (Levin, Momen, Drivdahl, & Simons, 2000). This metacognitive error is called *change blindness blindness*. Thus, simply asking persons for their own ability to detect changes is not possible; change detection performance has to be measured objectively. Therefore, research on individual differences has a high practical relevance, e.g., for driving, navigation, or surveillance (cf. O'Regan et al., 1999; Simons & Levin, 1998). A variety of heterogeneous studies indicated that individual differences in change blindness are associated, e.g. with age (e.g., Caird, Edwards, Creaser, & Horrey, 2005), with dispositional anxiety (McGlynn, Wheeler, Wilamowska, & Katz, 2008), expertise (Werner & Thies, 2000), or cultural differences (Humphreys, Hodsoll, & Campbell, 2005). For example, older adults detected less gradually appearing changes in driving scenes, that were taken from inside a car, than younger adults (Batchelder et al., 2003). Moreover, changes of photographs of womens' white Caucasian faces were detected faster by white Caucasians than by Indian Asians (Humphreys et al., 2005). The latter showed a better change detection performance for photographs of womens' faces of their own race in comparison to a foreign race. These studies serve as first empirical evidence for the existence of individual differences in change blindness, assessed with a variety of different experimental methods. Nevertheless, research on individual differences in change blindness is still in its infancy. The findings have never been put together into a holistic framework.

Moreover, it is unclear which underlying processes are associated with individual differences in change blindness. Former heterogeneous research has shown the existence of individual differences in attentional processes. For example, various studies confirm that people high in trait anxiety are faster in allocating their selective attention towards threatening stimuli than low anxious individuals (e.g., Bradley, Mogg, Falla, & Hamilton, 1998; Byrne & Eysenck, 1995; Mogg & Bradley, 2002). According to hypervigilance theory (Eysenck, 1992), anxious individuals are more distractible by any stimulus compared to nonanxious individuals, regardless whether a threat-related, emotional stimulus is presented or not. In the context of change detection, individual differences in attentional change processing might facilitate or complicate the detection of changes (McGlynn et al., 2008). For example, adults with high dispositional anxiety performed worse in detecting changes in real-world scenes without a snake when these scenes were preceded by scenes with a snake. According to the authors, anxious participants had more difficulties in disengaging their attention from fear eliciting scenes than non-anxious participants. Thus, individual differences in the allocation of selective attention may guide the way how changes are seen and encoded (McGlynn et al., 2008). Overall, it has been suggested that, from a theoretical point of view, individual differences in change blindness might result from capacity limitations of attention (cf. Cowan, 2000; Masuda & Nisbett, 2006; Rensink, 2000b; Simons & Ambinder, 2005).

The spatial allocation of attention is reflected by the N2pc component (e.g., Eimer, 1996). Also the size of the N2pc amplitude differed systematically between persons. Individual differences in the N2pc were mainly investigated in spatial cueing tasks, i.e. the occurrence of a target is preceded by a visual cue indicative of the target's location in the visual field. For example, the N2pc mirrored individual differences in self-esteem (H. Li et al., 2012). Participants had to report luminance changes of the fixation cross while social rejection cues, i.e. disgust faces, appeared simultaneously. The N2pc amplitude was enhanced when social rejection cues were presented for low self-esteemed adults compared to participants with high self-esteem. Moreover, in another spatial cueing task, differences in trait anxiety were visible in the size of the N2pc amplitude (Fox, Derakshan, & Shoker, 2008). When pictures of angry faces were presented, the N2pc amplitude was only enhanced for highly anxious individuals in comparison to low anxious individuals. To conclude, the N2pc amplitude might reflect individual differences in selective attention (cf. Eimer, 1996).

Second, individual differences were also observed in post-perceptual process. For example, past research has presumed a relationship of individual differences in cognitive abilities with working memory updating (e.g., Ecker et al., 2010; N. P. Friedman et al., 2006) or with working memory capacity (e.g., Ecker et al., 2010; Schmiedek, Hildebrandt, Lövdén, Wilhelm, & Lindenberger, 2009). These differences might be associated with individual differences in general decision making competencies, even in real-life circumstances (cf. Bruine de Bruin, Parker, & Fischhoff, 2007). On a conceptual level, one can say that in decision making, evaluative processes require an analysis of the qualitative fit of the decision with a specific individual goal in a feedback circuit (Gold & Shadlen, 2007). This performance monitoring is also linked to individual learning mechanisms. Furthermore, individual experiences or individual memory differences may affect priors and values, which themselves have an influence on the decision making process (Gold & Shadlen, 2007). In the context of change detection, individual differences in working memory updating or in decision making might explain possible differences between persons.

In line with this, the size of the P3 amplitude, reflecting post-perceptual processes (e.g., Koivisto & Revonsuo, 2003), also differed between persons in a multitude of studies. For example, in a clinical context, depressed patients showed an increased P3 amplitude compared to healthy participants (Kayser, Bruder, Tenke, Stewart, & Quitkin, 2000). The size of the P3 amplitude can even be treated as a predictor of a predisposition to alcoholism (Porjesz et al., 1998). Moreover, it was related to participants' personality. For example, the size of the P3 amplitude depended on participants' extraversion (e.g., Brocke, Tasche, & Beauducel, 1997; Daruna, Karrer, & Rosen, 1985; Stenberg, 1994). The relationship of the

P3 amplitude with participants' age is especially well-studied. Across an abundance of visual tasks, the P3 amplitude became smaller with increasing age (Fjell & Walhovd, 2003, 2004, 2005; L. Li et al., 2013; Lorenzo-López, Amenedo, Pascual-Marqui, & Cadaveira, 2008; for a review see D. Friedman, 2008). In the context of change detection, it was suggested that for a final decision whether a change occurred or not, the starting level of the perceptual accumulation process might vary as a function of individual differences (O'Connell et al., 2012).

The first main purpose of the present work was to systematically investigate individual differences in change blindness. As a second main aim, I intended to explore the underlying processes of individual differences in change blindness. Research on neurocognitive processes indicates that there are at least two processes which may prevent change blindness: the attentional change processing (N2pc) and post-perceptual processes (P3). Increased knowledge of these processes would allow for better explanations of change blindness and how it can be controlled in real life situations. To address these main research issues, three studies were carried out.

First, attentional processes and post-perceptual processes were fundamentally investigated in change blindness. Visual selective attention is necessary for successful change detection (e.g., Rensink et al., 1997). Attentional allocation is modulated by stimulus-driven bottom-up mechanisms (Jonides & Yantis, 1988) and by goal-directed top-down mechanisms (W. Schneider & Shiffrin, 1977). The allocation of attention is reflected by the N2pc component in the ERP (e.g., Eimer, 1996). It is unclear, however, how attention is allocated in change blindness. Therefore, bottom-up mechanisms and top-down mechanisms were manipulated separately to investigate the allocation of attention in change blindness and change detection, as reflected by the N2pc component (manuscript 1). Also post-perceptual mechanisms, i.e. a later phase of stimulus evaluation, necessary for ongoing decision making and action planning, play an important role in change blindness (e.g., Koivisto & Revonsuo, 2003). Post-perceptual processes in change blindness are reflected by the P3 component in the ERP (e.g., Koivisto & Revonsuo, 2003). However, how post-perceptual processes affect change detection remains questionable (e.g., Koivisto & Revonsuo, 2003). Hence, it was analyzed how varying task demands affected post-perceptual processes, as reflected by the P3 amplitude: In particular, manipulated task demands should affect working memory updating by the encoding of the motion signal of the change (cf. Verleger, 1988) for an aware representation of the change or the decision whether a change or not has occurred (cf. O'Connell et al., 2012). In this part of the present work, I will anticipate some findings from manuscript 3.

Second, based on these fundamental findings, another study intended to answer the question whether systematic individual differences exist in change blindness (manuscript 2). This study investigated the trait-like characteristic of individual differences in the sensitivity for changes. It was hypothesized that the sensitivity for changes is a consistent trait that can be defined as a variable which is stable across time, different situations, and methods (cf. McAdams, 1994, 1995). Therefore, the portion of variance which was due to a trait, due to the measurement occasion (state), or due to the experimental method was assessed by means of latent state-trait models (cf. Steyer et al., 1999). Moreover, it is important to know which cognitive processes contribute to individual differences in change blindness. First, it is unclear, how exactly spatial attention is allocated in change blindness. Thus, the allocation of attention was analyzed, reflected by the N2pc amplitude (cf. Eimer, 1996). In particular, I suggested that the effect of individual differences on change detection was biased differently by the way how observers search for the change (top-down) and by the number of distracting mudsplashes (bottom-up). Second, also post-perceptual mechanisms, as indicated by the P3 amplitude (cf. Koivisto & Revonsuo, 2003), should contribute to the explanation of individual differences in change blindness, e.g. reflecting individual differences in working memory updating or decision making (cf. Gold & Shadlen, 2007; O'Connell et al., 2012). In particular, individual differences in post-perceptual change processing should be more pronounced in highly demanding tasks.

Third, I intended to apply these observations on individual differences in change blindness and their underlying mechanisms to the example of cognitive aging (manuscript 3). Former research has consistently reported an age-related decline in change detection (e.g., Rizzo et al., 2009). To a certain extent, this age-related decline in change detection performance was caused by attentional-processes, as reflected by the N2pc component (Wascher, Schneider, Hoffmann, Beste, & Sänger, 2012). It remains unclear, however, how differences post-perceptual processes contribute to the explanation of age differences in change blindness. Therefore, the present work concentrated on a later stage of change processing. In particular, it was hypothesized that the negative relationship of age and the sensitivity for changes depended at least partially on differences in post-perceptual processes, as reflected by the P3 amplitude. An additional mediation analysis was performed to investigate this research question.

6 Methods

A longitudinal design allowed the investigation of the consistency of individual differences in change blindness across several measurement occasions. Overall, four measurement occasions were conducted. At measurement occasion one, two, and three, behavioral data and electrophysiological data were recorded while the change blindness task was conducted. At measurement occasion four, however, further measures were collected to assess the discriminant validity of the change blindness measures. Manuscript 1 and manuscript 2 are based on data from all three measurement occasions, whereas manuscript 3 refers to data from measurement occasion one only.

Seventy-four paid (8€/hour) volunteers from a community sample participated at measurement occasion one (38 women, 36 men, age between 18 and 73, mean age 40.1 years). 60 volunteers from the same sample (33 women, 27 men, aged between 18 and 73, mean age 40.5 years) participated at all four measurement occasions. However, in manuscript 1, only participants with at least 30 percent of correctly detected changes ($.30 \leq$ hit rate $\leq .82$) were included in the analysis to ensure a high signal-to-noise ratio by averaging across a sufficient number of trials for the N2pc per participant.

In change blindness tasks, it is possible to vary the degree of realism of the presented stimuli, depending on the research issue (Rensink, 2002). Simple stimuli are well-suited for the research of individual differences in change blindness as unwanted influences of other processes, e.g. of knowledge or interest, can be controlled for (cf. Jensen, Yao, Street, & Simons, 2011; Rensink, 2002). Moreover, change blindness paradigms may vary with respect to the number of repetitions of the change (cf. Rensink, 2002; Simons, 2000). In a *forced choice / one-shot* detection paradigm, the original and the modified scene are only presented only (e.g., Phillips & Singer, 1974; Simons, 1996, 2000). Hence, the presentation time of the stimuli is controlled and the accuracies for change and no-change trials as well as reaction times for correct and incorrect responses can be computed. Furthermore, influences of eye movements, effects of long-term memory are minimalized, and different experimental manipulations can easily be compared to each other (Rensink, 2002). In contrast to the use of other techniques, e.g. a blank screen, the presentation of mudsplashes, which are presented simultaneously with the change, has the advantage that confounding effects of iconic memory should stay unaffected (cf. Schankin & Wascher, 2008).

In the present work, simple stimuli were presented on a computer screen. They consisted of 81 dots arranged in a 9 x 9 matrix and presented on a black background. Forty of the dots were colored light gray, 40 dots were colored dark gray, and the dot in the center of the matrix was colored either green or blue. In a forced choice paradigm, change blindness was induced by white squares which served as mudsplashes, whose number (four, six, or eight) varied between conditions. An experimental trial is displayed in Figure 1.

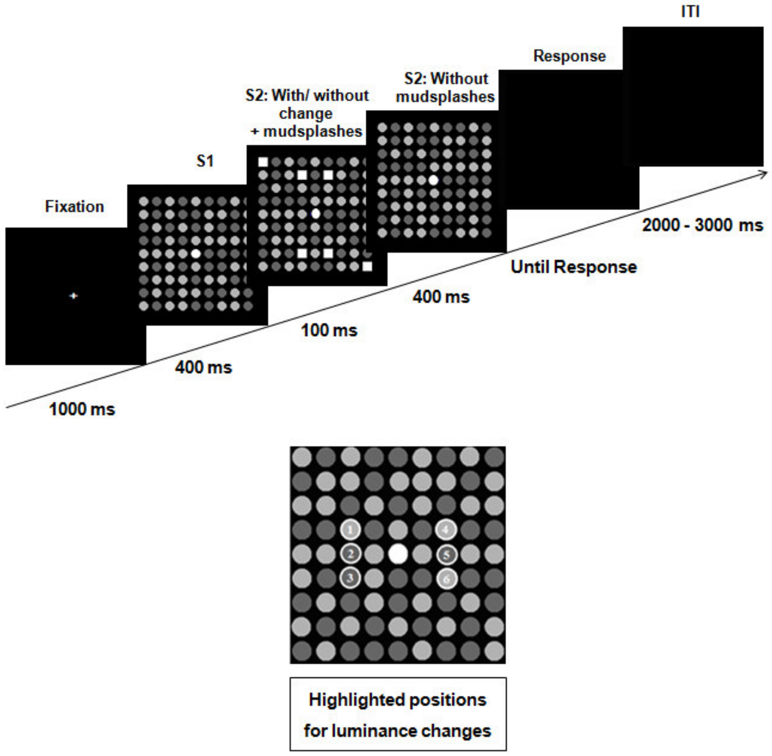

Figure 1. Example of an experimental trial (taken from Bergmann, Schubert, Hagemann, & Schankin, 2015). After a fixation cross (1000 ms), matrix S1 appeared (400 ms), followed by matrix S2 with a possible luminance change (100 ms), simultaneously with the mudsplashes. S2 remained on the screen for another 400 ms without mudsplashes. Afterwards, participants indicated whether they had seen a change or not. Finally, an inter-trial interval (ITI) of 2000 – 3000 ms appeared. In this example, six mudsplashes were presented.

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Each trial began with a fixation cross in the center of the screen, followed by the first matrix and then by the second matrix, simultaneously with the mudsplashes. Participants were instructed to indicate whether they had seen a possible luminance changes at six predefined positions or not by pressing a key.

There were four different experimental conditions**:** First, in the LOW-NUMBER-OF-MUDSPLASHES condition (also referred to as 4-MUDSPLASH condition in manuscript 2) four mudsplashes were presented. Second, the HIGH-NUMBER-OF-MUDSPLASHES condition (also referred to as 8-MUDSPLASH condition in manuscript 2) included the presentation of eight mudsplashes. Third, in the NOT-HIGHLIGHTED condition (also referred to as BASELINE condition in manuscript 2) six mudsplashes were shown. Fourth, in the HIGHLIGHTED condition, again six mudsplashes appeared and, in addition, change positions were permanently highlighted in red color (cf. Figure 1). In manuscript 1 and 3 the four conditions were summarized in two different analyses: The manipulation of attentional processes was investigated by varying the number of mudsplashes in a bottom-up analysis (LOW-NUMBER-OF-MUDSPLASHES VS. HIGH-NUMBER OF MUDSPLASHES condition) and by varying highlighted change positions in a top-down analysis (NOT-HIGHLIGHTED VS. HIGHLIGHTED condition). Similarly, task demands were manipulated: A decreased number of mudsplashes as well as highlighted change positions should simplify the task

EEG was continuously recorded from 25 Ag-AgCl electrodes, placed according to the international 10–20 system. During recording, all electrodes (F3, Fz, F4, T7, C3, C4, T8, Tp9, Tp10, P7, P3, Pz, P4, P8, PO7, PO8, O1, Oz, O2) were referenced to Cz. Fpz was used as ground. The N2pc was extracted from the ERP by subtracting the activity ipsilateral from those contralateral relative to the position of a change. The amplitude was measured as the mean activity at posterior electrodes about 300 ms after change onset (cf. Eimer, 1996; Luck & Hillyard, 1994a; Schankin & Wascher, 2007, 2008). The P3 amplitude was measured as mean activity in the time window from 400 to 600 ms after change onset. Data from a 3 x 4 electrode grid (F3, Fz, F4; C3, Cz, C4; P3, Pz, P4; O1, Oz, O2) were entered into further statistical analyses.

For the decision whether or not a change has occurred, signal detection theory (Green & Swets, 1966) constitutes an appropriate theoretical basis (cf. Gold & Shadlen, 2007). Observers’ accuracies in change detection were computed by means of this theory. To distinguish between differences in sensitivity and response bias, d’ (= z [p(*hit*)] – z [p(*false alarm*)]) and c (= -0,5*[z (p(*hit*)) + z (p(*false alarm*)]) were computed. Greater values of sensitivity d' show an increased sensitivity for changes. Greater values of response bias c indicate a more conservative response behavior compared to a more liberal responding.

In manuscript 1 and 3, I will summarize the results by reporting only effect sizes calculated by means of Hay's ω or Cohen's *d*. In manuscript 2, several different LST models were set up, separately for sensitivity *d'*, for the N2pc amplitude for detected changes, and for the P3 amplitude for detected changes (cf. Steyer et al., 1992). In each LST model, we used four manifest variables (LOW-NUMBER-OF-MUDSPLASHES, HIGH-NUMBER-OF-MUDSPLASHES, HIGHLIGHTED and NOT-HIGHLIGHTED condition) at three different measurement occasions, extended by three method factors (M-1 model; cf. Eid, 2000). Provided that the model fits were acceptable, the portion of variances of the manifest variables that are determined by their latent components was analyzed with the help of standard LST parameters (cf. Deinzer et al., 1995; Steyer et al., 1992). First, a *coefficient of trait specifity* (also referred to as *consistency*) describes the portion of variance which is due to the trait (T) [$\sigma^2(T)$ / $\sigma^2(Y)$]. Second, a *coefficient of occasion specifity* [$\sigma^2(S)$ / $\sigma^2(Y)$] includes the influence of the measurement occasion (S) and the person-situation interaction. Third, a *coefficient of method specifity* [$\sigma^2(M)$ / $\sigma^2(Y)$] describes the influence of the experimental method (M) and the person-method interaction. Fourth, a *coefficient of reliability*, which reflects the systematic, error-free measurement of the latent variables, can be quantified as sum of these measures [$\sigma^2(T) + \sigma^2(S) + \sigma^2(M)/\sigma^2(Y)$]. For a more detailed description of all data analyses, please see the methods and results section of manuscript 1- 3.

7 Cognitive change processing

First of all, it was investigated which cognitive processes are fundamental for change blindness and change detection. Past research has indicated that both attentional processes (e.g., Rensink et al., 1997) and post-perceptual processes (Koivisto & Revonsuo, 2003) play an important role in change detection. Thus, a change in one or in both of these processes may lead to change blindness. The first aim of the present work was to assess how systematic manipulations of these cognitive processes affected change detection.

7.1 The allocation of attention in change detection and change blindness (manuscript 1)

First, it was assessed how attention is allocated in change detection and change blindness. How stimuli are selected depends on both stimulus-driven *bottom-up* mechanisms and on goal-driven *top-down* mechanisms (for reviews see, e.g., Burnham, 2007; Corbetta & Shulman, 2002). Manipulating the salience of the change (e.g., Rensink, O'Regan, & Clark,

2000) or the way how observers search for the change (e.g., Rensink et al., 1997) influences change detection. We suggested that varying bottom-up mechanisms and top-down mechanisms separately might shed light on the question how attention is allocated in change detection and why change blindness occurs. In the present study, it was hypothesized that reducing the number of mudsplashes and thus increasing the salience of the change (bottom-up) as well as guiding observers' attention onto possible change positions by highlighting them (top-down) should increase participants' sensitivity for changes. These manipulations should also be reflected by the N2pc component in the ERP as an indicator of selective attention (cf. Eimer, 1996). We suggested that bottom-up and top-down mechanisms tap distinct neurocognitive processes. Reducing the number of mudsplashes should prepone the N2pc latency and decrease the N2pc amplitude (bottom-up), whereas highlighting change positions should only enhance the N2pc amplitude (top-down; cf. Brisson & Jolicœur, 2007; Kiss & Eimer, 2011; Mazza et al., 2009).

The results partially support our suggestions. Figure 2 of manuscript 1 displays the mean values and standard errors of the behavioral data. Successful change detection depended on both bottom-up and top-down mechanisms. More irrelevant distractors perturbed the allocation of attention onto the changes, $\omega^2 = .79$ (bottom-up). Guiding attention onto the change before its occurrence facilitated change detection, $\omega^2 = .92$ (top-down).

Figure 4 of manuscript 1 shows the differences waveforms of the N2pc component. An N2pc was observable only for detected changes, $d = .87$ (bottom-up), $d = 1.50$ (top-down). Different features of the N2pc were reflected by the experimental manipulation. Thus, different mechanisms of attentional allocation were affected. The N2pc peak latency, $\omega^2 =.15$, and the onset latency, $\omega^2 = .14$, were delayed when the number of mudsplashes increased (bottom-up). Highlighted stimuli elicited an N2pc component with earlier peak latency, $\omega^2 = .37$, and greater amplitude, $\omega^2 = .13$ (top-down). Together, the selection function of visual attention is explainable by limitations in capacity and/or in time. Bottom-up influences are only affected by the speed of the attention that is allocated onto a change. However, top-down mechanisms that also affect the speed of information processing may additionally decrease the effort which is necessary to allocate attention onto the change (cf. Gazzaley et al., 2008). It is still unclear, however, how ongoing post-perceptual processes influence change detection.

7.2 Post-perceptual change processing

Second, it should be explored how post-perceptual processes, i.e. a late phase of change processing, necessary for ongoing decision making and action planning (Koivisto & Revonsuo, 2003), were affected in a change blindness task. Post-perceptual change processing is reflected by the P3 amplitude in the ERP (Koivisto & Revonsuo, 2003). In the preceding study, we could show that more distracting mudsplashes or highlighted change positions in comparison to not-highlighted positions led to an increased sensitivity for changes. Thus, the difficulty of the task and therefore task demands were successfully manipulated by varied characteristics of the stimuli (cf. Pringle, Irwin, Kramer, & Atchley, 2001). We hypothesized that task demands had an effect on post-perceptual processes. In particular, less mudsplashes as well as highlighted change positions should lead to an increased sensitivity for changes, reflected by a larger P3 amplitude (cf. L. Li et al., 2013; Pringle et al., 2001; Verleger, 1988).

The results show that the P3 amplitude was greater for detected changes than for undetected changes reflecting an aware change detection (cf. Eimer and Mazza 2005; Koivisto and Revonsuo 2003; Schankin and Wascher 2007; Turatto et al. 2002). This change blindness effect of the P3 amplitude was enhanced when task difficulty was easier, i.e. for highlighted change positions in comparison to not-highlighted change positions, $\omega^2 = .12$, and when the number of mudsplashes was reduced, $\omega^2 = .01$. Moreover, the P3 amplitude, which was averaged across detected, undetected, and no changes, was increased when change positions were highlighted in comparison to not-highlighted change positions, $\omega^2 = .23$. And it was greater when the number of mudsplashes was decreased, $\omega^2 = .12$. In line with former research, we conclude that the size of the averaged P3 amplitude decreased with task difficulty, reflecting working memory updating (e.g., Verleger, 1988), possibly elicited by the transient motion signal of the change, or a goal-oriented aware decision process whether or not a change has occurred, determined by threshold-bound accumulation of perceptual evidence (O'Connell et al., 2012). Together, two processes were identified which were manipulated by the present change blindness task: attentional processes and post-perceptual processes. It is still, unclear, however, how these processes contribute to individual differences in change blindness.

8 Interindividual differences in change detection and change blindness (manuscript 2)

The second main aim of the present work was to assess whether individual differences in change blindness are a trait-like characteristic. A trait can be defined as a variable which is independent from the situation and the measurement method (e.g., McAdams, 1994, 1995). Methodological influences, e.g., different experimental conditions, situational variations, e.g. observers' varying degree of fatigue, or unsystematic measurement errors, i.e. random mistakes, may also contribute to individual differences in change detection. So far, no attempt has been made to integrate these assumptions into a single explanation. With the help of LST models, the trait specific variance of the sensitivity for changes, of the situation, of the method, and of measurement errors were estimated (cf. Steyer et al., 1992).

The first aim of the present work was to assess whether the sensitivity for changes was a trait. The LST model for sensitivity *d'* we set up fitted well with the data, $\chi^2(60) = 72.6$, $p = .128$, CFI = .74, RMSEA= .06. Figure 2 displays this model.

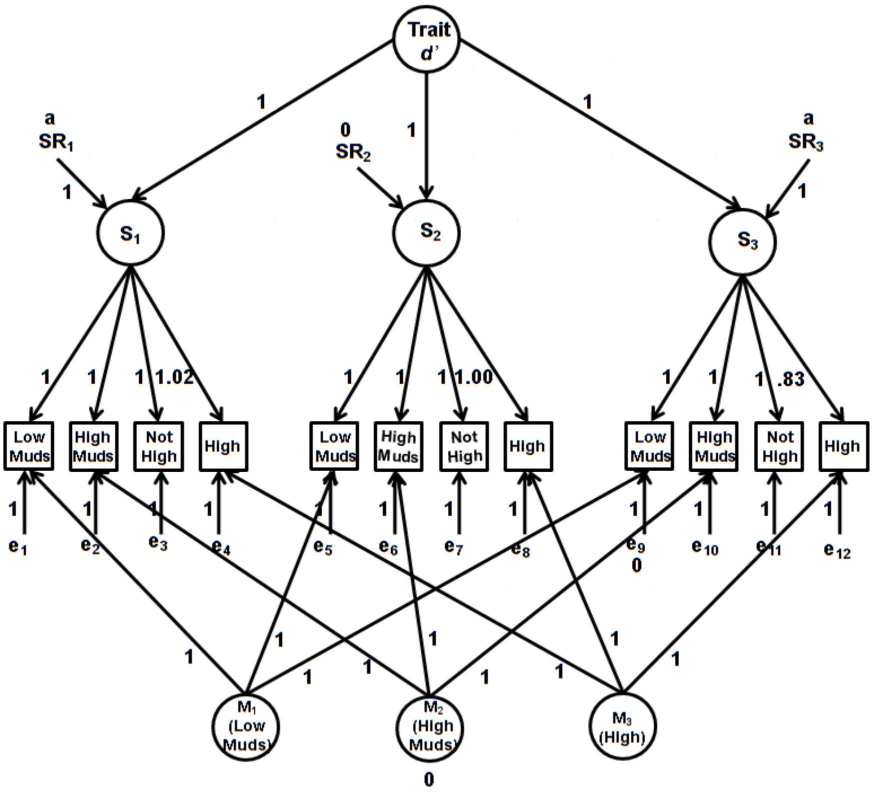

Figure 2. Latent state-trait model for sensitivity *d'*. The variance of the observed variables in the four conditions (Low Muds = LOW-NUMBER-OF-MUDSPLASHES condition, High Muds = HIGH-NUMBER-OF-MUDSPLASHES condition, Not High = NOT-HIGHLIGHTED condition, High = HIGHLIGHTED condition) was decomposed into situation (S_1–S_3), method (M_1–M_3) and measurement error (e). The variance of the situations was decomposed into state residuals (SR_1–SR_3) and into the latent trait (Trait *d'*).

Together, the results show that the sensitivity for changes is a stable trait, i.e. a person is consistently able to detect changes better than others, across different situation and measurement methods. 63% to 86% of the variance in the manifest measure of the sensitivity for changes was due to consistent individual differences in a latent trait (except for the HIGHLIGHTED condition). 0% to 14% of the variance was due to the situation, 0% to 10% of the variance was explainable by the experimental method, and 2% to 23% of the variance was attributable to measurement errors (cf. Table 6 in manuscript 2 for standard LST parameters). Trait specifities were comparable to the Big Five personality traits (cf. Deinzer et al., 1995). Low effects of the situation are attributable to observers' varying degree of motivation or fatigue (cf. Sänger & Wascher, 2011).The increased effect of the experimental method can be explained by a decreased task difficulty due to differences in attentional and post-perceptual processes (for a discussion see below). Low method specifities and high reliabilities suggest that technical measurement problems played a subordinate role for the assessment of individual differences in change blindness. Moreover, the sensitivity for changes showed a convergent and discriminant validity with respect to standard measures of personality and intelligence. One exception here is a small positive association between individual differences in the sensitivity for changes and general intelligence. This finding may tentatively suggest that measures of individual differences in change blindness and intelligence tap at least in part the very same cognitive process.

Second, another purpose of this study was to assess which neurocognitive processes contributed to individual differences in change blindness. Therefore, it was analyzed whether individual differences in successful change detection were associated with attentional processes (N2pc) or post-perceptual processes (P3). We set up two LST models, separately for the N2pc amplitude and for the P3 amplitude changes (please see manuscript 2 for figures of the LST models). Both LST-models were accepted as they fitted (marginally) with the data (N2pc, $\chi^2(61) = 65.9$, $p = .311$, CFI = .95, RMSEA = .04; P3, $\chi2(57) = 94.4$, $p = .001$, CFI = .95, RMSEA = .11).

When attentional processes were analyzed, 11% to 46% of the variance in the manifest measure of the N2pc was due to individual differences in a latent trait. 22% to 29% of the variance was explainable by the experimental method, but only when attention was guided onto possible changes in a top-down way in the HIGHLIGHTED condition (in all remaining conditions the method specifity was zero). Moreover, a positive relationship between individual differences in the N2pc and in the sensitivity for changes was found, $r = -.49$.

These findings suggest that individual differences in the allocation of selective attention contribute to individual differences in change detection (cf. Eimer, 1996). In particular, the effect of individual differences in the sensitivity for changes was decreased when observers' attention was guided onto potential changes in a top-down way.

When post-perceptual processes were analyzed, 46% to 83% of the variance in the manifest measure of the P3 amplitude was due to consistent individual differences in a latent trait. 8% to 9% of the variance was explainable by the experimental method, but only when task difficulty was very low in the HIGHLIGHTED condition (in all remaining conditions the method specifity was zero). There was a positive relationship between individual differences in the P3 and in the sensitivity for changes, $r = .41$. Thus, post-perceptual cognitive processes are also related to individual differences in change detection. In particular, the influence of individual differences in the sensitivity for changes was slightly decreased when the task was easiest in the HIGHLIGHTED condition.

Moreover, a stepwise regression indicated that the inclusion of the N2pc amplitude as a first predictor allowed explaining 19 % of the variance in the sensitivity for changes, whereas the amount of explained variance increased significantly to 29% after inclusion of the P3 amplitude as a second predictor. This observation suggests that the N2pc and the P3 component essentially tap distinct neurocognitive processes which both contribute to and amplify the individual sensitivity for changes.

In sum, the preceding section of the present work showed that a) individual differences in the sensitivity for changes are due to a trait, i.e. that one person is systematically more sensitive to detect changes than another person, across different situations and methods, b) that these individual differences in change detection are explainable to a great extent by attentional processes and by post-perceptual processes, c) that the influence of individual differences on the sensitivity for changes decreases when observers' attention is guided onto possible changes in a top-down way, and d) that individual differences in the sensitivity for changes are also less pronounced when decision making whether or not a change has occurred is easier (cf. Koivisto & Revonsuo, 2003; O'Connell et al., 2012). Next, I will apply these observations to the example of cognitive aging.

9 Individual differences in change blindness due to cognitive aging

In Germany, it has been discussed for years whether older adults should pass a second late driving test (e.g., Stockburger, 2012). It is well known that with increasing age people have more difficulties to drive a car safely. In driving, the detection of changes, e.g. of traffic signs or of the oncoming traffic, plays an important role. This example illustrates that cognitive aging might also be related to increased change blindness. Indeed, empirical evidence indicates that older adults have more difficulties in detecting changes than younger adults (e.g., Rizzo et al., 2009). This might be due to a variety of impaired cognitive operations, which are associated with advanced age (Craik, 1994). Behavioral studies revealed that cognitive functions, such as selective attention, inhibitory control of distracting inferences, a less efficient working memory, or a decreased working memory capacity deteriorate with normal aging (D. Friedman, 2008; Hasher & Zacks, 1988; Craik & Salthouse, 2008; Dempster, 1992; Dobbs & Rule, 1989). For example, older adults have difficulties in ignoring irrelevant stimuli (Kok, 2000). This reduced inhibitory control may also contribute to an age-related decrease in the efficiency of working memory operations (Hasher & Zacks, 1988). Past research recorded a cognitive decline from the age of 60 in several working memory operations, e.g., in digit span forward or backward tasks reflecting working memory storage capacity (Dobbs & Rule, 1989). This age-related decline was also explained by a reduced flexibility of cognitive processing operations (Dobbs & Rule, 1989).

In the context of change detection, it remains unclear, however, which specific processes underlie the age-related decrease in change detection performance. Theoretically, a change in any or all cognitive processes may lead to a decline of change detection performance in normal aging. In the present work, I will focus, firstly, on age differences in attentional processes, and second on age differences in post-perceptual processes in change blindness.

9.1 Age-related differences in the attentional change processing

The enhanced liability to change blindness in older adults (e.g., Costello et al., 2010; Rizzo et al., 2009) might be based on deficits in attentional deficits. Indeed, studies that focused on the impact of aging and attentional processes in change detection have shown that change blindness increased with age (Caird et al., 2005; Rizzo et al., 2009; Wascher et al., 2012). If spatial attention played an important role in explaining age differences in change detection, this should be reflected by the N2pc component. This was the case in a recent change blindness study by Wascher et al. (2012). In this study change blindness was induced by a short blank between two subsequent visual frames. Two bars presented left and right to a fixation cross served as stimuli. A change was defined as following: a) The luminance of one bar changed, b) the orientation of one bar changed, c) the luminance and the orientation of the same bar changed, and d) the luminance of one bar and the orientation of the other bar changed in the perceptual conflict condition. Participants were instructed to press the button at the location, either where the luminance change occurred and to ignore the irrelevant orientation change in one block, or where the orientation change occurred and to ignore the irrelevant luminance change in another block. Only in the perceptual conflict condition an N2pc was observable, which was increased toward luminance changes for older adults compared to younger adults under both instructions. That is, older adults showed an increased attentional orientation towards luminance changes. According to the authors, older adults were not capable to compensate their initial attentional distraction by the more salient stimulus. They seemed to have more difficulties in maintaining an intentional allocation of attention toward relevant characteristics of the stimuli than younger adults.

9.2 Age-related differences in the P3 amplitude in change blindness (manuscript 3)

Not only attentional processes, but, also evaluative, post-perceptual processes may explain age-related differences in change blindness. However, the effect of aging on post-perceptual cognitive processes has never been assessed before. Post-perceptual processes are reflected by relatively late ERP components, such as the P3 (e.g., Koivisto & Revonsuo, 2003). The P3 is one component in the ERP, which is consistently affected by age. Across a variety of studies, its amplitude was decreased for older adults (e.g., L. Li et al., 2013; Lorenzo-López et al., 2008). Therefore, it was concluded that deficits in working memory updating cause age-related cognitive dysfunctions, which might also affect ongoing decision making and action planning in change blindness. Age differences in the change blindness effect on the P3 amplitude, i.e. the difference between detected and undetected changes, should mirror differences in post-perceptual processes of conscious change evaluation (cf. Koivisto & Revonsuo, 2003). In the present study, a group of middle-aged adults was included to analyze a trajectory of age effects in contrast to most previous aging studies. The main aim of the present study was to investigate whether the negative relationship of age and the sensitivity for changes was mediated by post-perceptual processes, as reflected by the amplitude of the P3. Age-related differences in the sensitivity for changes and in the P3 amplitude may also depend on task demands, which affected the difficulty of the task (cf. paragraph 7.2. of the present work).

There were two central age-related findings. First, behaviorally, the sensitivity for changes decreased only in older age, $\omega^2 \geq .206$. (This age difference was visible in particular when task demands were lowest, i.e. when change positions were highlighted. Presumably, older adults benefited less from highlighting change positions than middle-aged or younger adults). Electrophysiologically, however, the change blindness effect on the P3 amplitude, i.e. the difference between detected and undetected changes, was present in younger participants, $\omega^2 \geq .38$, but already absent in middle-aged participants, $\omega^2 \leq .01$ (cf. Figure 5 of Manuscript 3; Bergmann et al., 2015). Thus, the interpretation of the P3 effect as reflecting an aware identification of the change or processes necessary for the report of a change do not fit the data very well. Alternatively, we suggest that this effect on the P3 amplitude can be interpreted as reflecting observers' subjective confidence in their own ratings (cf. Eimer & Mazza, 2005). Consequently, younger participants' increased confidence in their own ratings might have caused a greater P3 amplitude in comparison to less confident middle-aged or older participants.

Second, there was no general age-related decline in the P3 amplitude when averaged across detected, undetected, and no changes, $\omega^2 \leq .00$. That is, a general change in post-perceptual cognitive processes that are reflected by the averaged P3 amplitude like working memory updating (e.g., Verleger, 1988), cannot explain the effect of age on the sensitivity for changes. Thus, further cognitive processes may contribute to age differences in change detection and change blindness. This hypothesis that that the negative relationship of age and the sensitivity for changes was only partially mediated by post-perceptual processes was tested in the following paragraph in more detail.

9.3 Mediation analysis

To further test the hypothesis whether age differences in the sensitivity for changes are mediated by post-perceptual stimulus processing as reflected by the P3 amplitude, we applied a mediation model X → Z → Y (Baron & Kenny, 1986). This model indicates that the effect of the independent variable (X = age) on the dependent variable (Y = sensitivity *d'*) is, at least to a certain extent, mediated by a third variable (Z = P3 amplitude). Data from Pz were entered into this analysis because the effect of change blindness on the P3 amplitude was most pronounced at this electrode site. Because post-perceptual processes, as reflected by the P3 amplitude, differ between detected and undetected changes (e.g., Koivisto & Revonsuo, 2003; L. Li et al., 2013; Niedeggen et al., 2001; Turatto et al., 2002), separate mediation analyses were performed for the P3 activity in trials in which participants detected changes and failed to detect them. We analyzed separately for each experimental condition (i.e., BASELINE, 4-MUDSPLASH, 8-MUDSPLASH, and HIGHLIGHTED condition) if the indirect effect of age on sensitivity *d'* was mediated by the P3 amplitude with bootstrapped confidence intervals. This effect is significant if the confidence interval does not include zero. We used bootstrapped 95%-confidence intervals (2,000 bootstrap samples), based on a non-parametric bootstrap procedure provided in the SPSS script by Preacher and Hayes (2004).

It should be noted, however, that a bootstrap-based mediation analysis does not take into account that models other than a complete or a partial mediation might exist, which could provide a better explanation for the observed covariance structure of age, sensitivity, and the P3 amplitude. Therefore, the fit of alternative models has to be tested (L. R. James, Mulaik, & Brett, 2006). Thus, we combined the bootstrap-based mediation analysis with structural equation modeling, following the recommendation of Danner, Hagemann, & Fiedler (2015), which is based on work by different other authors (e.g., MacKinnon & Luecken, 2008; MacCallum, Wegener, Uchino, & Fabrigar, 1993). With structural equation modeling the variances of the observed manifest variables can be decomposed into error-free latent variables, measurement errors, and residuals.

As a first advantage, this approach allows for the representation the dependent variable and the mediator as latent variables, i.e. we used one set of variables as indicators of the dependent variable and one set of variables as indicators of the mediator and extract a latent factor for each of two sets of variables. The advantage here is that, on the one hand, in the present study the influence of different experimental conditions on the operationalization of sensitivity to changes and on P3-related post-perceptual processes is reduced and, on the other hand, measurement errors can be controlled (Bollen, 1989). Second, alternative causal models of the trivariate system can be compared to each other (e.g., MacCallum et al., 1993). Statistically implausible models, which do not fit the empirical data, can be excluded (e.g., L. R. James et al., 2006). In the current study, twelve predefined, theoretically plausible effect models were computed (cf. Figure 3).

Thus, the relationship between the latent dependent variable Sensitivity (Y), measured by different manifest indicators of the single experimental conditions, the latent mediator P3 Amplitude (Z), separately for detected or undetected changes, and the manifest independent variable Age (X) were assessed. We included only those experimental conditions as indicators for sensitivity and P3 amplitude (i.e. BASELINE, the 4-MUDSPLASH, THE 8-MUDSPLASH) which became significant in the bootstrap analyses. Age was treated as a manifest, continuous variable. We used the generalized least squares discrepancy function (GLS; Hu & Bentler, 1998), implemented in AMOS 20.0 (Arbuckle, 2006) to estimate the model parameters.

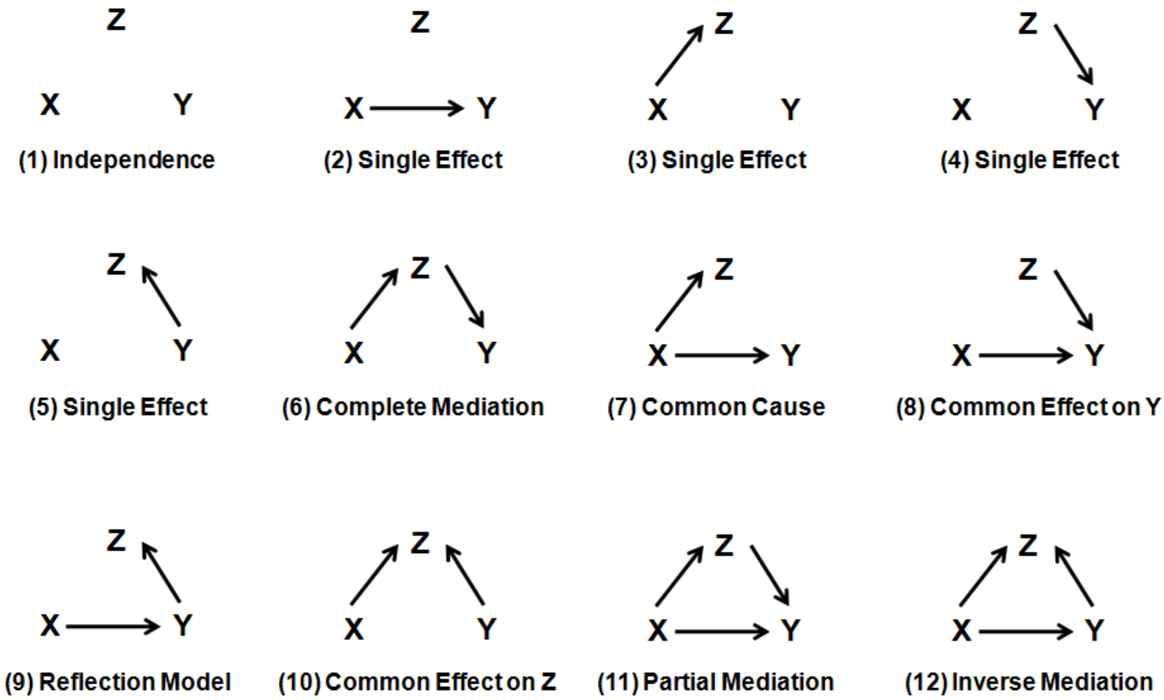

Figure 3. The twelve predefined effect models (cf. Danner et al., 2015).

Overall, five missing values were replaced by the mean of the respective condition. The critical ratio and its standard error were used to assess the significance ($\alpha \leq .05$) of each model parameter. The general model fit was evaluated with the χ^2 statistic, the comparative fit index (CFI; Bentler, 1990), and the root mean square error of approximation (RMSEA; Browne &

Cudeck, 1992). Finally, we compared nested models with χ^2 difference scores to identify the model with the best fit (Danner et al., 2015).

First, we analyzed with bootstrapped confidence intervals if the effect of age on the sensitivity for changes was mediated by the P3 amplitude X → Z → Y (Preacher & Hayes, 2004). Eight analyses were computed with age (X) as independent variable, sensitivity for changes (Y) as dependent variable, and P3 amplitude (Z) as mediator, separately for each experimental condition and separately for detected and undetected changes (i.e., four analyses for detected changes: BASELINE, 4-MUDSPLASH, 8-MUDSPLASH, and HIGHLIGHTED condition; four analyses for undetected changes: BASELINE, 4-MUDSPLASH, 8-MUDSPLASH, HIGHLIGHTED condition). If the effect was significant, the respective condition has been used as an indicator in the following structural equation modeling. For detected changes, the effect was significant in the BASELINE condition, CI = [-.0091; -.0005], in the 4-MUDSPLASH condition, CI = [-.0188; -.0039], and in the 8-MUDSPLASH condition, CI = [-.0137; -.0010]. In the HIGHLIGHTED condition, however, no effect was observed, i.e., the confidence interval included zero, CI = [-.0065; .0026)]. For undetected changes, however, there was only a significant effect in the 4-MUDSPLASH condition, CI = [-.0129; -.0004], whereas it did not reach significance in the BASELINE condition, CI = [-.0084; .0000], in the 8-MUDSPLASH CONDITION, CI = [-.0063; .0004], and in the HIGHLIGHTED condition, CI = [-.0042; .0004)]. In summary, we found an effect in three experimental conditions (i.e. BASELINE, 4-MUDSPLASH, and 8-MUDSPLASH condition) for detected changes, whereas we only found an effect in the 4-MUDSPLASH condition for undetected changes.

Because the bootstrap-based mediation analysis only tests for a complete or partial mediation, which might not fit the empirical data best, alternative models were assessed by structural equation modeling (cf. Figure 6). As the analysis of underlying effect models with latent variables requires at least two manifest indicators for each latent variable, only models for detected changes, but not for undetected changes were specified. The latent variable Sensitivity was decomposed into three manifest indicators, into three measurement errors that are specific for each indicator, and, in the case that Sensitivity was regressed on the P3 Amplitude or on Age, into a latent residual. Because no mediation effect was observed in the bootstrap analysis of the highlighted condition, this condition was excluded from structural equation modeling. Consequently, only the following indicators of Sensitivity remained in the model (cf. Figure 7): mean sensitivity *d'* of the *Baseline Condition* (Y_1), the *4-Mudsplash Condition* (Y_2), and the *8-Mudsplash Condition* (Y_3). Similarly, the latent variable P3 Amplitude was decomposed into three manifest variables, into three measurement errors, and, in the case that the P3 Amplitude was regressed on Sensitivity or on Age, into a latent residual. Hence, for the P3 Amplitude, the *Baseline Condition* (Z_1), the *4-Mudsplash Condition* (Z_2), and the *8-Mudsplash Condition* (Z_3) were set up as indicators.

We followed the recommendations by Danner et al. (2015) and relaxed four path coefficients, first, between the mediator P3 Amplitude and its indicators 4-Mudsplash Condition and 8-Mudsplash Condition and, second, between Sensitivity and its indicators 4-Mudsplash Condition and 8-Mudsplash Condition. All other path coefficients were set to one. As a consequence of insignificance, the variance of the measurement error of the P3 amplitude for the 4-Mudsplash Condition (ε_2) in all models was set to zero.

In structural equation modeling some models are statistically but not theoretically plausible. Therefore, researchers always have to take into account which models can be excluded solely based on theoretical arguments (Danner et al., 2015). Table 1 shows the model fits of twelve predefined effect models.

In the current experiment, participants always behaviorally responded after the occurrence of the P3 amplitude in the event-related potential. Thus, it seems plausible that cognitive processes, reflected by the P3 amplitude, influence the sensitivity *d'* and not vice versa. Based on this theoretical assumption, the *Single Effect* model 5 (Sensitivity → P3 Amplitude), the *Reflection* model, the *Common Effect on Z* model, and the *Inverse Mediation* model were not considered further. The *Partial Mediation* model provided the best model fit, $\chi^2(13) = 16.9$, $p = .205$, CFI = .937, RMSEA = .064, BIC = 81.4. It differed significantly from all remaining models, i.e. the *Independence* model, $\Delta\chi^2_{\text{Difference}}(3) = 18.5$, $p < .001$, the *Single Effect model No. 2* (Age → Sensitivity), $\Delta\chi^2_{\text{Difference}}(2) = 14.6$, $p < .001$, the *Single Effect model No. 3* (Age → P3 Amplitude), $\Delta\chi^2_{\text{Difference}}(2) = 18.5$, $p < .001$, the *Single Effect model No. 4* (P3 Amplitude → Sensitivity), $\Delta\chi^2_{\text{Difference}}(2) = 12.9$, $p = .002$, the *Complete Mediation* model, $\Delta\chi^2_{\text{Difference}}(1) = 7.0$, $p = .008$, the *Common Cause* model, $\Delta\chi^2_{\text{Difference}}(1) = 7.6$, $p = .006$, and the *Common Effect on Y* model, $\Delta\chi^2_{\text{Difference}}(1) = 7.9$, $p = .005$.

Table 1. The fit of twelve predefined effect models, analyzed with structural equation modeling (cf. Danner et al., 2015).

No	Models	χ2	*df*	*p*	CFI	RMSEA	BIC
1	**Independence Model(X,Y,Z)**	35.4	16	.004	.685	.129	87.0
2	**Single effect (X→Y)**	31.5	15	.007	.732	.123	87.5
3	**Single Effect (X→Z)**	35.4	15	.002	.669	.136	91.3
4	**Single Effect (Z→Y)**	29.9	15	.012	.759	.116	85.8
5	**Single Effect (Y→Z)**	29.9	15	.012	.759	.116	85.8
6	**Complete Mediation (X→Z→Y)**	23.9	14	.048	.840	.098	84.1
7	**Common Cause (X→Z,X→Y)**	24.5	14	.039	.829	.102	84.8
8	**Common Effect On Y (X→Y,Z→Y)**	24.8	14	.037	.825	.103	85.0
9	**Reflection Model (X→Y→Z)**	19.1	14	.163	.918	.070	79.3
10	**Common Effect On Z (X→Z,Y→Z)**	29.2	14	.010	.754	.122	89.4
11	**Partial Mediation (X→Z,Z→Y,X→Y)**	16.9	13	.205	.937	.064	81.4
12	**Inverse Mediation (X→Z, X→Y,Y→Z)**	16.9	13	.205	.937	.064	81.4

Note. X = age; Y = sensitivity *d‘;* Z = P3 amplitude size for detected changes.

In summary, the Partial Mediation model was the best to explain the underlying covariance structure of the independent variable Age (X), the mediator P3 Amplitude (Z), and the dependent variable Sensitivity (X). That is, the observed effect of age on the sensitivity for changes is partially explained by age differences in post-perceptual processes, as reflected by the P3 amplitude. Figure 4 shows the final model. All path coefficients reached significance, all *p*s ≤ .05.

Together, by means of an additional mediation analysis, we assessed to what extent post-perceptual processes (reflected by the P3 amplitude) contributed to age-related differences in the sensitivity for changes. This analysis further confirmed the interpretation that the P3 amplitude might reflect participants' confidence in their own ratings. It showed that the effect of age on the sensitivity for changes was mediated by the P3 amplitude when changes were detected but not when they remained unnoticed. These results are in accordance with previous findings. First, the influence of confidence on undetected (or no) change trials was smaller than on detected change trials (cf. Eimer & Mazza, 2005). And second, the same

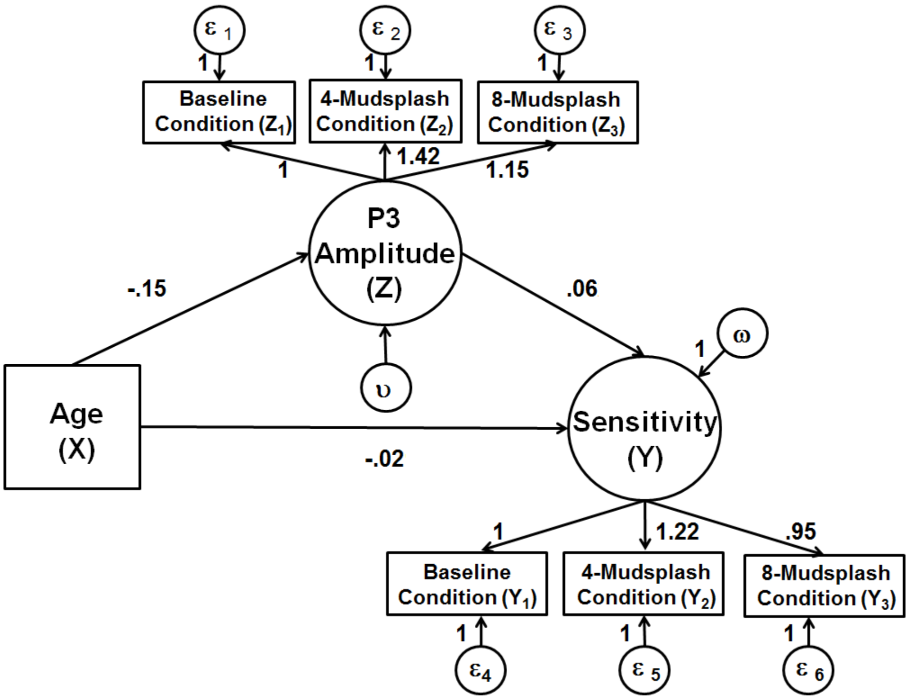

Figure 4. Partial mediation model. Three indicators were assessed for the latent mediator P3 Amplitude (Z) for detected changes and three indicators for the latent dependent variable Sensitivity (Y). Besides, we set up the manifest independent variable Age (X), the residual of the P3 Amplitude (υ), the residual of Sensitivity (ω) and six measurement errors ($\varepsilon_{1\text{-}6}$) (for details see text).

authors also reported a relationship between confidence and performance in the change blindness task, namely that higher confidence led to a higher accuracy rate in a change detection task. However, confidence in change detection can explain only in part the effect of age on change detection performance only. Statistically, the partial mediation model fitted the observed covariance structure best. Thus, further cognitive processes contribute to age differences in change detection and change blindness, possibly attentional processes (cf. Wascher et al., 2012).

Together, the present chapter showed that both attentional processes (cf. Wascher et al., 2012) and postperceptual processes (manuscript 3) contribute to age differences in change blindness. In particular, the age-related decrease in the sensitivity for changes can be partially explained by confidence in the own ratings.

10 Discussion

To conclude, the present work was the first to systematically investigate individual differences in change blindness in a longitudinal design. The results show a) the existence of systematic individual differences in the sensitivity for changes and b) that these differences are explainable by two distinct neurocognitive processes to a considerable amount: earlier attentional processes (N2pc) and later post-perceptual processes (P3).

A first fundamental study investigated the allocation of attention in change blindness. This study indicated that selective attention is a capacity-limited emergent property (cf. Desimone & Duncan, 1995), which is influenced by both bottom-up (e.g., Jonides & Yantis, 1988) and top-down mechanisms (e.g., W. Schneider & Shiffrin, 1977). Bottom-up mechanisms became visible only in the speed of attention (N2pc latency). However, top-down mechanisms were observable in both the processing speed (N2pc latency) and, in addition, in the amount of attention which was allocated onto the change (N2pc amplitude). Both mechanisms enhance the probability for a successful representation of the change in memory (Gazzaley, Cooney, McEvoy, Knight, & D'Esposito, 2005). Moreover, task difficulty was manipulated to explore how post-perceptual processes affected change detection. More mudsplashes as well as not highlighted change positions in comparison to highlighted positions led to difficulties in working memory updating (e.g., Verleger, 1988) for an aware representation of the change or to a more complex decision making process whether a change or not has occurred (O'Connell et al., 2012).

In a second study, the trait-like characteristic of individual differences in change detection and its underlying processes were investigated. The results show that the sensitivity for changes is a trait, i.e. one person is consistently more sensitive to changes than another person, across time and experimental methods. Moreover, both attentional processes (N2pc amplitude) and post-perceptual processes (P3 amplitude) independently contributed to the explanation of individual differences in change blindness. Thus, I suggest, firstly, that individual differences in change blindness can be attributed to the observers' individual limitation of attentional capacity (cf. Masuda & Nisbett, 2006; Simons & Ambinder, 2005), which varies systematically between persons (e.g., Cowan, 2000; Rensink, 2000b). In contrast to bottom-up mechanisms, top-down biased attention reduced the effect of individual differences on change detection. Thus, the trait-like characteristic of the sensitivity for changes played a more subordinate role in change detection. For example, specific trainings (cf. Simons & Ambinder, 2005) might override the trait-specific effect on change detection to a certain extent and improve the sensitivity for changes, also for poor performers. Second, individual differences in the awareness of change detection are also explainable by differences in working memory capacity (cf. Ecker et al., 2010; Nittono, Nageishi, Nakajima, & Ullsperger, 1999; Schmiedek et al., 2009), necessary for the processing and evaluation of the change for ongoing decision making (Gold & Shadlen, 2007; cf. Koivisto & Revonsuo, 2003; O'Connell et al., 2012). The trait-specific influence of the sensitivity for changes was decreased when the task was much easier. Therefore, individual differences in the evaluation of a change or in decision making are slightly decreased when task demands are low. Critically, our model for individual differences in the P3 amplitude fitted only marginally with the data. For future research, I recommend manipulating post-perceptual processes differently, e.g. by systematically varying working memory load. Confounding effects of the attentional manipulation should be reduced that way.

However, it should be noted that the attentional and post-perceptual change processing cannot completely explain individual differences in the sensitivity for changes. Further mechanisms could possibly contribute to the ability to detect changes. For example, it might be interesting to investigate individual differences not only in the N2pc and P3 amplitude, but also in the latency of these components in change blindness. In this way the influence of bottom-up biased activation on individual differences in change detection could be analyzed in more detail. Moreover, ERP latency measures are associated with general intelligence (e.g., Houlihan, Campbell, & Stelmack, 1994; Schubert, Hagemann, Voss, Schankin, & Bergmann, 2015; Pelosi et al., 1992). Thus, these measures may account for the observed relationship between general intelligence and the sensitivity for changes.

Practical implications of the present findings, e.g. for driving, navigation, or surveillance are obvious (cf. O'Regan et al., 1999; Simons & Levin, 1998). It can be concluded that (professional) operations demanding on change detection, may distinguish between low and high performers in a variety of different situations and across time. This in turn has implications for the improvement of the design of visual environments allowing changes, e.g. modified signs in road traffic, also to be detected by persons with low change detection ability, e.g. by car drivers who have more problems in detecting important changes on the road than others. Focusing the drivers' attention to highlighted dangerous crossings before the vehicle passes these or conducting specific driver trainings to enhance drivers' expertise might override the influence of low change detection ability leaving the trait effect to play only a subordinate role in safe driving. However, the link between a decision and a specific action is not mandatory (Gold & Shadlen, 2007). It is unclear whether the present conclusions about post-perceptual processes in the current simple decision making task can be transferred to more complex decision making in real-life, i.e. the deliberation of a variety of alternatives (Gold & Shadlen, 2007). Together, further research about the predictive validity of change blindness tasks for real-life decision making in change detection is necessary. Ultimately, it might be possible to use change blindness tasks for the diagnosis of (professional) aptitude of operations demanding the sensitivity for changes, e.g., of surgeons, pilots, or truck drivers.

In a third study, the present findings of individual differences in change blindness were applied to the example of cognitive aging. It is well known that with increasing age people have more difficulties to detect changes, e.g. in car driving (Caird et al., 2005). Former research has shown that attentional processes contribute to age differences in change blindness (Wascher et al., 2012). Thus, the current study investigated whether age-related individual differences in the sensitivity for changes (e.g., Rizzo et al., 2009) were mediated by post-perceptual processes. The results show that post-perceptual processes can explain age differences in change blindness in part. The interpretation of the P3 effect as reflecting an aware identification of the change or processes necessary for the report of a change did not fit the data very well. Therefore, it was interpreted as the observers' confidence in their own ratings (cf. Eimer & Mazza, 2005). In particular, the age-related decline in change detection performance was partially due to older adults' decreased confidence in the own ratings. Only in the easiest condition, i.e. when changes were highlighted in red color, the relationship between age and the sensitivity for changes was not mediated by post-perceptual processes. This is again in line with the observation that individual differences in change blindness are most pronounced in more demanding tasks. From a practical point of view, I suggest that a regular training of critical situations, e.g. in road traffic, should developed to improve older adults' confidence in their own decision making and strengthen possible compensation mechanisms.

11 Summary and conclusion

The present work shows the existence of systematic individual differences in change blindness. It can be concluded that the sensitivity for changes is a trait. That is, persons differ in their ability to detect changes, independent from the situation or the measurement method. Moreover, there are two explanations for individual differences in change blindness: a) capacity differences in visual selective attention (cf. Cowan, 2000; Rensink, 2000b) that may be influenced by top-down activated attention helping to focus attention onto relevant stimuli

b) differences in working memory capacity (cf. Ecker et al., 2010) or in decision making (cf. O'Connell et al., 2012). In accordance with this, age-related individual differences in the sensitivity for changes can be explained by attentional processes (Wascher et al., 2012) and by confidence in the own ratings. Together, the present work might form the basis for a more application-oriented research on individual differences in change blindness and its underlying processes.

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Appendix A1 – manuscript 1

THE ALLOCATION OF ATTENTION IN CHANGE DETECTION AND CHANGE BLINDNESS

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Abstract

Visual change detection often fails when observers' attention is distracted by some other visual disruption in the environment that occurs simultaneously with the change. This phenomenon is called change blindness. For successful change detection, selective attention is necessary. The aim of the current experiment was to manipulate the allocation of attention in change blindness. Therefore, the number of distracting stimuli was varied (bottom-up) or possible change positions were highlighted (top-down). Participants were asked to report changes of colored dots. The N2pc component in the event-related potential was measured as an indicator of the allocation of attention. The sensitivity for changes increased when the number of mudsplashes was reduced or change positions were highlighted. Only for detected changes, an N2pc was found. The N2pc latency was delayed when the number of mudsplashes increased. Highlighted stimuli elicited an N2pc component with earlier latency and enhanced amplitude. Together, bottom-up processes become visible in the latency and top-down processes are mainly mirrored by the amplitude of the N2pc. That is, successful change detection depends on the properties of distracting and changing objects, which determine the speed and intensity of the allocation of attention toward a change.

Keywords: Change blindness, Selective Visual Attention, Bottom-Up, Top-Down, N2pc Amplitude, N2pc Latency

The allocation of attention in change detection and change blindness

The limited capacity of the visual system in perceiving and representing the environment has been impressively demonstrated by a phenomenon known as change blindness—the failure to detect even major changes in scenes when they occur simultaneously with other visual disruptions (Simons & Levin, 1997).

Visual selective attention

Most researchers agree that visual selective attention is the crucial process underlying change detection and change blindness (e.g., Beck, Rees, Frith, & Lavie, 2001; Eimer & Mazza, 2005; Rensink, O'Regan, & Clark, 1997; Simons, 2000). It has been shown, for example, that a change was detected the better the closer the eyes were to the location of a change (O'Regan, Deubel, Clark, & Rensink, 2000). Complementary, directing attention toward a change location by a cue presented before the occurrence of a change prevented from change blindness (Lamme, 2003). It is unclear however, how exactly visual-spatial attention is allocated in change blindness. Therefore, the aim of the present study was to investigate which mechanisms had an influence on the allocation of attention in change detection and change blindness. First, we show that there are two possible main mechanisms that affect the allocation of selective attention (*bottom-up* bias and *top-down* bias). Second, it is introduced how the allocation of attention in change blindness can be measured by means of the N2pc component in the event-related potential (ERP).

Bottom-up and top-down mechanisms

Attentional selection leads to faster and / or more accurate stimulus processing. How stimuli are selected depends on both a stimulus-driven *bottom-up* mechanism and a goal-driven *top-down* mechanism (for reviews see e.g., Burnham, 2007; Corbetta & Shulman, 2002). Perceptually salient stimuli attract observers' attention bottom-up in a fast and automatic way, quite independent from observers' intentions. For example, a unique or strikingly colored target in an otherwise homogeneous array of distractors or an object that appears suddenly in the visual field capture visual attention (e.g., Jonides & Yantis, 1988; Theeuwes, 1994). Attentional allocation is modulated by a top-down mechanism, which is deliberate and controlled in guiding attention toward information that is relevant for the current individual goal. Thus, contextual information, instructions, observers' intentions, or expectancies bias voluntary control (e.g., Desimone & Duncan, 1995). It should be noted, however, that top-down biased attention may be interrupted by stimulus characteristics (Müller & Rabbitt, 1989) as well as that bottom-up mechanisms can be modulated by goal-oriented processes (Folk, Remington, & Johnston, 1992).

In the context of change detection, knowing more about these processes would allow better predictions about which changes are perceived and how change blindness could be controlled in real life situations. We propose two mechanisms that determine the probability of change detection, namely features of the change a) relative to other visual disruptions and b) relative to other non-changing objects. In the following, we describe these mechanisms in more detail. Usually, changes in the visual environment produce a transient motion signal. This signal is so salient that it attracts attention automatically and thus increases the probability of an aware representation of the change. If, however, additional visual distractors, such as a blank screen (e.g., Rensink et al., 1997; Rensink, O'Regan, & Clark, 2000) or small mudsplashes (e.g., O'Regan, Rensink, & Clark, 1999) occur at the same time, the salience of the motion signal is reduced. In this case, change detection depends on how the visual environment is scanned by the observer. This scanning path again depends on the actual salience of a changing object. In this case, however, salience is defined by the similarity of the changing object relative to other objects in the environment. The probability that an observer directed its attention to the object while it is changing is the higher the more salient (i.e. outstanding) an object is. In addition, intentions, motivation, contexts, and previous experiences of the observer play an important role. To distinguish between these different mechanisms of attentional allocation in the current study, we refer to bottom-up processes whenever a process is related to the salience of the change and to top-down processes when a process is related to intentions and experiences of the observer.

There is only some research, which proves the mechanisms of this model. First, the role of bottom-up processes becomes apparent when the salience of the change is manipulated. A few studies showed that change detection declined when the salience of the change was reduced. For example, the salience of the motion signal is smaller when the inter-stimulus interval (i.e. the blank) is longer. Accordingly, change detection performance was reduced with longer inter-stimulus intervals (Phillips & Singer, 1974). Similarly, observers performed worse when the duration of the change itself decreased (Rensink et al., 2000). Furthermore, local transient signals of mudsplashes cause a smaller change blindness effect than a global transient signal of a blank screen (cf. Rensink et al., 2000).

Second, change detection also depends on the way how observers search for a change (top-down). The search strategy depends on the task-relevance of objects within a scene. Accordingly, changes of objects of central-interest were detected faster than those of marginal-interest (e.g., O'Regan et al., 2000; Rensink et al., 1997, 2000). Also the semantical meaningfulness of the change to the observer had an impact on attentional allocation (e.g., Fletcher-Watson, Leekam, Turner, & Moxon, 2006; Werner & Thies, 2000). For example, semantic changes of meaningful football scenes were detected faster than non-semantic changes, and more interestingly, football experts were more sensitive to changes in domain-related, semantic photographs than were novices (Werner & Thies, 2000). Finally, change detection performance also improved when attention was guided by a preceding cue which points to the change so that observers were able to allocate their attention intentionally to the change location (Becker, Pashler, & Anstis, 2000; Lamme, 2003).

However, this research on bottom-up and top-down processes has some limitations that should be noted at this point. First, per definition the salience of the change depends on the properties of the distractors (i.e. the visual interruption that occurs simultaneously with the change). So far, these bottom-up effects have been investigated either by varying the duration of a blank screen (Phillips & Singer, 1974; Rensink et al., 2000) or by comparing the effects of local signals of mudsplashes with those of a global signal of a blank screen (Rensink et al., 2000). These manipulations are confounded, however, with effects of iconic memory which provide an alternative explanation for the change blindness effect. When the presentation of the screen is interrupted, e.g. by a blank screen, the original image has to be stored in memory and finally be compared to the changed image (cf. Schankin & Wascher, 2008; Simons, 2000). Second, when the transient signal of the change is perturbed, changes are detected only when attention is deployed onto the right location (top-down). Most studies that investigated top-down processes manipulated observers' allocation of attention by varying the interestingness of the change (e.g., O'Regan et al., 2000) or the semantical importance or meaningfulness of the scene (e.g., Werner & Thies, 2000). However, these manipulations are confounded with observers' characteristics, i.e. unwanted influences of long term experiences such as knowledge or personal interests. These unwanted influences may affect the focussing of attention between observers in an unsystematic way and lead to an underestimation of the observed effects of top-down processes on change blindness performance. In summary, it is still not fully understood how attention is allocated in change detection and change blindness.

Therefore, the main purpose of the current study is to investigate the role of bottom-up and top-down processes in change detection and change blindness. This research question can only be answered if both mechanisms are manipulated separately within an otherwise highly similar paradigm. In the current study, we use mudsplashes to induce change blindness, whereby iconic memory should be left unaffected. We then manipulate either the number of mudsplashes to investigate the relationship between change and other visual distractions or highlight potential change positions to investigate the relationship between the change and other non-changing objects. First, increasing the number of mudsplashes should only reduce the salience of the change and thus diminish a more automatic capture of attention by the change. Accordingly, reducing the number of visual distractors should enhance the salience of the change and thus lead to an automatic capture of attention by the change. Second, guiding observers' attention onto the change before its occurrence prevents from change blindness (Lamme, 2003). Thus, permanently highlighted potential change positions should help observers to focus attention already before the occurrence of a change in a top-down way and thus reduce effects of change blindness, but without involving observers' individual motivation or expertise.

The N2pc component

However, manipulating different mechanisms of attentional allocation experimentally results in similar effects on a behavioral level, namely in a variation in change detection performance. Thus, it is unclear whether the experimental manipulation indeed tapped into the intended mechanism. ERPs allow a more fine-grained analysis of the specific processes underlying these effects. One component of the ERP, which is sensitive to the attentional selection of visual stimuli, is the N2pc. The N2pc occurs about 200 to 300 ms after stimulus onset contralateral to the stimulus location at posterior electrodes. Therefore, this component indicates that observers' directed their attention to a particular location in space (Eimer, 1996; Luck & Hillyard, 1994a, 1994b). In change detection tasks, an N2pc is evoked by changed stimuli that received some attention. As attention is a prerequisite for visual awareness, an N2pc was observed, for example, when participants reported changes in face expressions (Eimer & Mazza, 2005), in meaningful objects (Busch, Dürschmid, & Herrmann, 2010), or in colored dots (Schankin & Wascher, 2007).

The N2pc is also sensitive to effects of bottom-up and top-down mechanisms on the allocation of attention (e.g., Mazza, Turatto, & Caramazza, 2009; Zhao et al., 2011). So far, these effects were mainly investigated in visual search tasks. In these tasks, participants are asked to find a target presented among a number of distractors. First, manipulations of bottom-up effects are reflected in a change in amplitude and / or latency of the N2pc component. For example, Zhao et al. (2011) manipulated the salience of the target by increasing the color disparity between target and distractors. They showed that the N2pc amplitude was greater when color disparity was higher, i.e. the salience of the target was enhanced. In contrast, differences in color intensity affected the latency but not amplitude of the N2pc component, with an earlier onset for more intense stimuli (Brisson, Robitaille, & Jolicœur, 2007). Other researchers found that the N2pc component was affected by display size and distractor color (Mazza et al., 2009). In particular, the N2pc amplitude was greater when the number of irrelevant stimuli was enhanced reflecting the identification of the target by its enhancement. Moreover, heterogeneous distractors compared to homogeneous arrays caused a smaller N2pc amplitude and a preponed and longer lasting N2pc, reflecting the withdrawal of attention before it is shifted to the actual target (Mazza et al., 2009).

Second, the N2pc component was also modulated when the top-down guidance of attention was manipulated. Top-down mechanisms of attentional allocation are reflected by the N2pc amplitude. For example, Eimer (1996) investigated whether the attentional selection, as reflected by the N2pc component, is biased by bottom-up or top-down processes. Participants were asked to search for a target that differed with respect to its form, its color, or its word meaning from the distractors. Moreover, in the form and color discrimination task, the number of stimuli was varied: Either one target and three distractors or one target and one distractor were presented. The N2pc was elicited when the target item did not automatically pop out, i.e. when only one distractor was presented, indicating that it was not exclusively biased by stimulus-driven bottom-up effects. Most importantly, an N2pc was also elicited by the target when target and distractors differed semantically, that is with respect to their word meaning, reflecting the top-down controlled enhancement of the target (Eimer, 1996). Similarly, when a visual search task was combined with a spatial cueing paradigm, the contingency of cue and target was also obligatory for the top-down based elicitation of an N2pc component by the target (Eimer & Kiss, 2008, 2010; Kiss & Eimer, 2011). For example, in one study participants were asked to search for a small or a large target while some medium-sized distractors were presented (Kiss & Eimer, 2011). Before the presentation of the search displays, arrays of cues were shown. Uninformative with respect to the succeeding target location, one of their items varied in its size just like the target or was entirely absent. When no cue was presented, both small targets and large targets automatically elicited an N2pc (bottom-up guided attention). When a cue was shown, however, an N2pc was triggered by the target only when the size of the cuing stimulus matched the size of the target (top-down guided attention). It was concluded that top-down activity, for example search goals and task settings, determined the size of the N2pc amplitude and thus the controlled attentional selection of the target (Kiss & Eimer, 2011).

In summary, bottom-up mechanisms are reflected by the latency *and / or* amplitude of the N2pc component, whereas top-down mechanisms are mirrored by the N2pc amplitude only. Whether the latency or the amplitude of the N2pc component is affected by bottom-up mechanisms depends on the color disparity between target and distractors (N2pc latency; Brisson et al., 2007), on the number of distracting stimuli (N2pc amplitude; Mazza et al., 2009), and on the homogeneity of the distractor array (N2pc latency and N2pc amplitude; Mazza et al., 2009).

The present study

The main aim of the present study is to assess the role of bottom-up and top-down guidance of visual-spatial attention in a change blindness paradigm. The way of attentional allocation onto the change is manipulated experimentally: On a behavioral level, reducing the number of distracting mudsplashes should improve change detection performance because observers' attention should be less distracted from the change location (bottom-up). Highlighting potential change positions and thus guiding observers' attention before the occurrence of the change should also increase participants' sensitivity for changes (top-down). To assess whether this experimental manipulation indeed taps into different mechanisms of attentional allocation the electro-cortical activity is measured. Therefore, the N2pc component of the ERP is analyzed as an indicator of observers' attentional allocation (e.g., Luck & Hillyard, 1994a, 1994b). On the basis of previous research we hypothesize that the bottom-up capture of attention is reflected by the latency and by the amplitude of the N2pc component, whereas top-down mechanisms are only observable in the N2pc amplitude (cf. Brisson et al., 2007; Kiss & Eimer, 2011; Mazza et al., 2009). In particular, we hypothesize that, firstly, if the number of mudsplashes indeed affects the salience of a change so that attention is shifted to the change in a rather *bottom-up* manner, the N2pc latency should be shorter and the N2pc amplitude should be smaller when fewer distracting mudsplashes are presented. Second, if observers are able to focus their attention *top-down* on potential change locations, the amplitude of N2pc component should be larger.

Methods

Participants

Seventy-eight paid (8€/hour) volunteers from a community sample participated in the experiment. Participants were recruited via newspaper advertisement and web portals. Only participants with at least 30 percent of correctly detected changes averaged across all conditions (.30 ≤ hit rate ≤ .82) were included into the analyses to ensure a high signal-to-noise ratio by averaging across a sufficient number of trials for the N2pc per participant. Thus, 31 participants remained in the sample (15 women, 16 men, aged between 18 and 69, mean age 35.9 years). Three participants were left-handed, 27 were right-handed and one of them was bimanual. All of them reported normal or corrected to-normal vision and had normal color vision as measured with the Ishihara test of color blindness. Before the experiment started, all participants gave their written informed consent. The study was carried out in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and its amendments.

Apparatus & Stimuli

Participants sat in a comfortable armchair in a sound-attenuated chamber, which was dimly lit and electrically shielded. Two keys on a keyboard served as response buttons. The left key was marked in red and the right key in green color. They were located under participants' left and right index finger. Stimuli were presented on a 17-in. computer screen, placed 82 cm in front of the participants, at the center of their field of vision. The screen was set to a resolution of 1280 x 1024 pixels and a screen refresh rate of 60 Hz.

Stimuli consisted of 81 dots which were arranged in an imaginary 9 x 9 matrix (3.42° x 3.42° of visual angle) and presented on a black background (L = 0, a = 0, b = 0 in L*a*b color space). Forty of the dots were colored light gray (L = 73, a = 0, b = 0), 40 dots were colored dark gray (L = 42, a = 0, b = 0), and the dot in the center of the matrix was colored either green (L = 34, a = -38, b = 39) or blue (L = 34, a = 58, b = -105). The distance between single dots was .10° and their diameter was .28°. The distribution of the light and dark gray dots was balanced in the matrix so that accumulations of dots with equal luminance were avoided (cf.

Figure 1). In this way, nine matrices were created, which were used for all experimental conditions equally often. In Block 3 light red (L = 73, a = 38, b = 42) and dark red (L = 42, a = 61, b = 55) dots replaced six of the gray dots (cf. Figure 1).

White squares (L = 100, a = 0, b = 0) served as *mudsplashes*, whose number (four, six, or eight) varied between conditions. Each mudsplash (.28° x .28°) occluded exactly one gray dot. The mudsplashes never appeared in immediate vicinity to each other or to a change. Half of the mudsplashes were presented to the left and half to the right visual hemifield. Relative to their distance to the center, they were always presented symmetrically, mirrored along the vertical axis. Fifteen possible arrangements of their spatial positions were constructed in advance and then quasi-randomly ordered per block so that the same arrangement of mudsplashes never appeared more than three times consecutively.

Procedure

Each trial began with a fixation cross in the center of the screen, which lasted 1,000 ms (cf. Figure 1). Then, the first matrix (S1) appeared for 400 ms. Subsequently, the second matrix (S2) was presented for 100 ms, simultaneously with the mudsplashes. Then, the mudsplashes disappeared and the matrix remained on the screen for another 400 ms. On about 43% of the trials, S1 and S2 were identical (no change trial), on about 43% of the trials, one lateral dot changed its luminance at one of six possible locations (luminance change trial, cf. Figure 1), and on about 14% of all trials, the colored dot in the center changed its color (color change trial). Color changes were used to keep participants' attention fixed to the center of the screen. These trials excluded from further analyses because in this condition no change blindness effect can be observed (cf. Schankin & Wascher, 2008). Figure 1 shows the three dots of position 1, 2, and 3, (left hemifield) and the three dots of position 4, 5, and 6 (right hemifield). On half of the luminance change trials, the dot changed from dark gray to light gray, on the other half from light gray to dark gray. Similarly, on half of the color change trials, the central dot changed from green to blue, on the other half from blue to green. Finally, an inter-trial interval (ITI) of variable length (2,000 – 3,000 ms) followed.

Participants were instructed to indicate if they had seen a change or not by pressing the green or red key, respectively. The assignment of response keys was counterbalanced across participants. It was stressed that they should report a change only when they really saw it, and that guessing was not allowed.

There were four experimental conditions (cf. Table 1). First, in the LOW-NUMBER-OF-MUDSPLASHES condition, four mudsplashes were presented. Second, in the HIGH-NUMBER-OF-MUDSPLASHES condition, eight mudsplashes were shown. Third, in the NOT-HIGHLIGHTED condition, six mudsplashes were presented. Fourth, in the HIGHLIGHTED condition, also six mudsplashes were presented and in addition, the six possible positions of luminance changes were permanently marked in red color.

These four experimental conditions were presented in three blocks. First, in the NUMBER-OF-MUDSPLASHES block, either four (LOW-NUMBER-OF-MUDSPLASHES condition) or eight mudsplashes (HIGH-NUMBER-OF-MUDSPLASHES condition) were presented simultaneously with the change. Second, in the NOT-HIGHLIGHTED block, only the NOT-HIGHLIGHTED condition was presented. Third, in the HIGHLIGHTED block, only the NOT-HIGHLIGHTED condition was shown. The NOT-HIGHLIGHTED condition and the HIGHLIGHTED condition were presented in separate blocks to exclude interference effects by the highlighted change positions on following trials. This separation, however, was not considered necessary for the LOW- and HIGH-NUMBER-OF-MUDSPLASHES conditions, which were presented in one block therefore. Within a block, all trials were shown in random sequence with the following constraints. At maximum three luminance changes, three no changes, three changes of the same (left or right) side or two color changes appeared successively. Furthermore, the same matrix never appeared more than three times consecutively. In this way, four different trial sequences were created for each block and systematically assigned to participants. Short breaks of individual length always appeared after about seven minutes. After each block, there was a longer break.

Overall, three measurement occasions were conducted. On each measurement occasion, the experiment started with a short demonstration of all possible changes. On each change position, one exemplary change appeared in slowed presentation time and without any mudsplashes to ensure that all possible changes had been seen once by the participants. Then participants passed a short exercise of 91 trials (42 luminance changes, 42 no changes and 7 color changes). In the exercise, six mudsplashes were presented. Three experimental blocks followed. To prevent sequence effects, the sequential presentation of the experimental blocks was varied across measurement occasion. At measurement occasion one, participants started with the NOT-HIGHLIGHTED block, continued with the number of mudsplashes block and finished with the HIGHLIGHTED block. On the second measurement occasion, first the

HIGHLIGHTED block was presented, then the not HIGHLIGHTED block, and finally THE-NUMBER-OF-MUDSPLASHES block. Measurement occasion three started with the number of mudsplashes block, followed by the HIGHLIGHTED block and then by the NOT-HIGHLIGHTED block.

Each of the four experimental conditions consisted of 9 (matrices) x [4 (color changes) + 12 (luminance changes) + 12 (no changes)] x 3 (measurement occasions) = 756 trials with 316 luminance changes, 316 no changes and 108 color changes each. Altogether, this resulted in 3024 trials per participant.

EEG Recording

EEG was continuously recorded from 25 Ag-AgCl electrodes, placed according to the international 10–20 system. During recording, all electrodes (F3, Fz, F4, T7, C3, C4, T8, Tp9, Tp10, P7, P3, Pz, P4, P8, PO7, PO8, O1, Oz, O2) were referenced to Cz. Fpz was used as ground. Vertical electro-oculogram (EOG) was recorded bipolarly from above and below the right eye and horizontal EOG from the outer canthi of the eyes. Electrode impedances were kept below 5 kΩ. EEG was sampled with a rate of 1000 Hz. The signal was amplified by two BrainAmp DC amplifiers (Brain Products, Munich, Germany) with a band-pass of 0.1 – 250 Hz. Data was filtered off-line with a band-pass filter of 0.1 – 12 Hz and re-referenced to linked mastoids. EEG data were segmented into time windows of 1,700 ms, starting 200 ms prior to S1 and ending 1,400 ms afterward. Baseline was corrected relative to the activity of the interval 200 ms prior to S1 to 0 ms (-600 to -400 ms prior to S2). Ocular artifacts were corrected according to the algorithm of Gratton, Coles, and Donchin (1983). Trials with amplitudes lower than .5 µV in an interval of 100 ms, exceeding +/- 70 µV, or with a voltage step of 100 µV/ms were excluded from the data as artifacts.

Data Analysis

Behavioral data. *Hits* (percentage of correctly detected luminance changes) and *false alarms* (percentage of reported changes on no-change trials) were computed separately for each of the four experimental conditions, averaged across all three measurement occasions. To distinguish between differences in sensitivity and response bias, *d*' and *c* were calculated according to the signal detection theory (Green & Swets, 1966).

Electrophysiological data. The N2pc was extracted from the ERP by computing the ipsilateral and contralateral activity for each of the four experimental conditions. This resulted in eight ERP waveforms per participant. Grand average waveforms were inspected and the time window which reflected the maximal moment of contra-ipsilateral difference ± 25 ms was defined as measurement window for each condition. Table 1 shows the mean values for the N2pc onset and peak latencies and for the N2pc amplitude. The N2pc amplitude was measured as the mean amplitude difference between contra- and ipsilateral activity from 290 to 340 for the LOW-NUMBER-OF-MUDSPLASHES condition, from 340 to 390 for the HIGH-NUMBER-OF-MUDSPLASHES condition, from 310 to 360 ms for the NOT-HIGHLIGHTED condition, and from 280 to 330 for the HIGHLIGHTED condition, relative to change onset (S2; cf. Eimer 1996; Luck & Hillyard, 1994a, 1994b; Schankin & Wascher, 2007, 2008). Data from PO7/PO8 were entered into further statistical analyses because the N2pc was maximal at these electrode positions. To determine both peak-latencies and 50% onset-latencies, we followed the recommendations by Miller, Patterson, and Ulrich (1998) and applied the jackknife method. This method estimates the between subjects' variance by transiently excluding each participant from the computation (cf. Miller, Patterson, & Ulrich, 1998). Basically, it is based rather on peak detection of grand-average than on single-subject waveforms. Thus, it accurately estimates ERP latency differences between experimental conditions and has the advantage that it improves the signal-to-noise ratio.

Statistical Analysis of Bottom-up Effects. Bottom-up processes were investigated by manipulating the number of mudsplashes. To assess the effect of bottom-up processes, the LOW-NUMBER-OF-MUDSPLASHES condition and HIGH-NUMBER-OF-MUDSPLASHES condition were compared. Effects on sensitivity and response bias were tested by separate repeated-measures ANOVAs with the within-subjects' factor condition (LOW- vs. HIGH-NUMBER-OF-MUDSPLASHES), for *d'* or *c*, respectively. The effects on the N2pc amplitude were assessed by a repeated-measures ANOVA with the within-subjects' factors condition (LOW- vs. HIGH-NUMBER-OF-MUDSPLASHES) and change detection (detected vs. undetected). Effects on the N2pc latency were assessed on the basis of jackknifed data. Two repeated-measures ANOVAs were calculated with the within-subjects' factor condition (LOW- vs. HIGH-NUMBER-OF-MUDSPLASHES), separately for the N2pc peak latency and the N2pc onset latency.

Statistical Analysis of Top-down Effects. The influence of top-down mechanisms on attentional allocation was assessed by comparing the NOT-HIGHLIGHTED with the HIGHLIGHTED condition. In both conditions, six mudsplashes were presented but potential change locations were highlighted or not. A repeated-measures ANOVA was calculated with the within-subjects factor condition (NOT-HIGHLIGHTED, HIGHLIGHTED condition) for *d'* or *c*, respectively. Effects of the N2pc amplitude were assessed by a repeated-measures ANOVA with the within-subjects factors condition (NOT-HIGHLIGHTED, HIGHLIGHTED condition) and change detection (detected, undetected). A repeated-measures ANOVA was calculated with the within-subjects factor condition (NOT-HIGHLIGHTED, HIGHLIGHTED condition) for the N2pc peak latency or the N2pc onset latency, respectively.

All *F*-values of the ANOVAs on jackknife data were adjusted (Ulrich & Miller, 2001). Moreover, all statistics were adjusted by Greenhouse-Geisser epsilon correction for nonsphericity if the number of factor levels exceeded two. In this case, uncorrected degrees of freedom but corrected *p* values are reported. If indicated, additional post hoc analyses were calculated. In case of multiple comparisons, *p* was adjusted according to Bonferroni. Effect sizes were calculated by means of Hay's ω or Cohen's *d*.

Results

Bottom-up Effects on Change Detection

Bottom-up processes of attentional selection were manipulated by the number of mudsplashes (four vs. eight mudsplashes). We hypothesized that the sensitivity for changes enhances with decreasing number of mudsplashes because observers' attention should be less distracted from the change location. This effect should be reflected by the amplitude and latency of the N2pc component.

Behavioral data. In the LOW-NUMBER-OF-MUDSPLASHES condition, participants detected 51.0% (SEM = 2.9%) of the luminance changes and responded correctly to 96.2% (SEM = .7%) of the no changes. In the HIGH-NUMBER-OF-MUDSPLASHES condition, they detected 35.6% (SEM = 2.7%) of the luminance changes and rejected 95.5% (SEM = .7%) correctly as no changes. With increasing number of mudsplashes, participants were less sensitive for changes, $F(1,30) = 112.1$, $p < .001$, $\omega^2 = .79$, and responded more conservatively, $F(1,30) = 46.8$, $p < .001$, $\omega^2 = .60$ (Figure 2). However, sensitivity *d'* and response bias *c* were not related to each other in both conditions, as indicated by insignificant correlations (LOW-NUMBER-OF-MUDSPLASHES: $r = -.19$, $p = .300$; HIGH-NUMBER-OF-MUDSPLASHES: $r = .03$, $p = .892$).

Electrophysiological data. Figure 3 shows grand-averaged ERP waveforms evoked by the second stimulus display at posterior electrodes (PO7/PO8) contralateral and ipsilateral to the side where the change was presented, separately for detected and undetected changes. In Figure 4, difference waveforms of the N2pc are displayed.

The amplitude of the N2pc differed between detected and undetected changes, as indicated by a main effect of change detection, $F(1,30) = 17.5$, $p < .001$, $\omega^2 = .36$. The N2pc did not differ in its amplitude when the number of mudsplashes changed. That is, the main effect of condition was not significant, $F(1,30) < 1.0$. The interaction of condition and change detection did not reach significance, $F(1,30) < 1.0$. Next, it was tested whether the N2pc component was observable for undetected changes at all. A t-test showed that an N2pc was only present for detected changes, $t(30) = 5.0$, $p < .001$, $d = .87$, but absent for undetected changes, $t(30) < 1.0$. Thus, the following analyses refer to detected changes only. Both the peak latency, $F_c(1,30) = 6.2$, $p = .019$, $\omega^2 = .15$, and the onset latency, $F_c(1,30) = 5.7$, $p = .023$, $\omega^2 = .14$, were delayed with a larger number of mudsplashes.

Top-down Effects on Change Detection

The influence of top-down processes on change blindness and on the N2pc component was assessed by comparing the NOT-HIGHLIGHTED with the HIGHLIGHTED condition. We hypothesized that when change positions are permanently highlighted, observers should be more sensitive to changes because they should be able to better focus their attention on potential change locations. This effect should be reflected by the N2pc amplitude only.

Behavioral data. In the HIGHLIGHTED condition participants responded correctly to 87.5% (SEM = 1.9%) of the luminance changes and to 96.9% (SEM = .6%) of the no changes. In the NOT-HIGHLIGHTED condition participants responded correctly to 46.3% (SEM = 2.5%) of the luminance changes and to 93.7% (SEM = 1.2%) of the no changes. Comparing both conditions, participants were more sensitive, $F(1,30) = 352.2$, $p < .001$, $\omega^2 = .92$, and responded more liberally when potential change positions were permanently highlighted in red color, $F(1,30) = 56.7$, $p < .001$, $\omega^2 = .65$. However, sensitivity *d'* and response bias *c* were not related to each other in both conditions, as indicated by insignificant correlations (NOT-HIGHLIGHTED condition, $r = .27$, $p = .142$; HIGHLIGHTED condition, $r = -.13$, $p = -.488$).

Electrophysiological data. The amplitude of the N2pc differed between detected and undetected changes, as indicated by a significant main effect of change detection, $F(1,30) = 42.2$, $p < .001$, $\omega^2 = .58$. The main effect of condition was marginal significant, $F(1,30) = 3.7$, $p = .065$, $\omega^2 = .08$. However, the interaction of condition and change detection was significant, $F(1,30) = 4.6$, $p = .040$, $\omega^2 = .11$. Post hoc tests indicated that the N2pc amplitude for detected changes was enhanced for highlighted change positions compared to not highlighted change positions, $F(1,30) = 11.5$, $p = .004$, $\omega^2 = .13$. For undetected changes, however, no difference between both conditions was observed, $F(1,30) < 1.0$. Next, it was tested whether the N2pc component was elicited by undetected changes at all. A t-test showed that an N2pc was only present for detected changes, $t(30) = 8.3$, $p < .001$, $d = 1.50$, but absent for undetected changes, $t(30) < 1.0$. Thus, the following analyses of the N2pc refer to detected changes only. The N2pc peaked earlier when positions were highlighted, $F_c(1,30) = 18.7$, $p < .001$, $\omega^2 = .37$, whereas the effect on the onset latency did not become significant, $F_c(1,30) < 1$.

Discussion

Previous research has shown that changes in our visual environment are detected only when they receive some attention (e.g., Beck et al., 2001; Eimer & Mazza, 2005; Rensink et al., 1997; Simons, 2000). The allocation of visual selective attention is biased by two mechanisms, a stimulus-driven bottom-up mechanism and a goal-driven top-down mechanism (e.g., Burnham, 2007; Desimone & Duncan, 1995). In the current study we wanted to investigate the role of these mechanisms in the allocation of attention in a change blindness paradigm in order to gain a more comprehensive understanding of this phenomenon. Both mechanisms were manipulated experimentally within an otherwise highly similar paradigm. Change blindness was induced by distracting stimuli (i.e., mudsplashes) that occurred simultaneously with the change (cf. O'Regan et al., 1999). By using mudsplashes, confounding effects of iconic memory were avoided (cf. Schankin & Wascher, 2008). In order to experimentally manipulate the allocation of visual selective attention, either the number of mudsplashes was varied (bottom-up mechanism) or possible change locations were highlighted (top-down mechanism).

Bottom-up and top-down mechanisms

Observers' sensitivity for changes should be modulated by both bottom-up and top-down mechanisms. Increasing the salience of the change by reducing the number of mudsplashes or attracting observers' attention onto possible change positions before the occurrence of the change should decrease the effect of change blindness. This was indeed the case in the current experiment: On the behavioral level, participants' sensitivity for changes increased both when the number of distracting mudsplashes was reduced (bottom-up) and when potential change positions were permanently highlighted in red color (top-down).

The N2pc component

If these experimental manipulations affected the sensitivity for changes via different mechanisms, this should be reflected by the N2pc component as an indicator of observers' attentional allocation (e.g., Luck & Hillyard, 1994a, 1994b). On the basis of previous findings, we hypothesize that the bottom-up capture of attention is reflected by the latency and by the amplitude of the N2pc (Mazza et al., 2009) whereas top-down mechanisms should mainly be observable in the N2pc amplitude (e.g., Kiss & Eimer, 2011). In particular, we hypothesized that, first, if the number of mudsplashes indeed affected the salience of a change in a bottom-up way, the N2pc latency should prepone and the size of the N2pc amplitude should be smaller when fewer distracting mudsplashes are presented. Second, if observers are able to focus their attention top-down onto potential change locations, the amplitude of the N2pc component should be greater.

This was partly the case in the present study. Varying the number of mudsplashes was reflected by the (peak and onset) latency of N2pc, with a delayed occurrence of the N2pc component with an increasing number of distracting stimuli. In contrast, when potential change locations were highlighted, the amplitude and peak latency were affected, with a greater amplitude and an earlier peak latency. That is, different features of the N2pc were sensitive to the experimental manipulation, indicating that, as intended, different mechanisms of attentional allocation were affected. However, it should be stressed that the way how these features varied across experimental conditions were only partially as expected. These findings are discussed in more detail in the following.

First, we manipulated bottom-up processes by the salience of the changing stimuli relative to distracting ones. As hypothesized an increased salience of the change was associated with an earlier onset and peak latency of the N2pc component (e.g., Brisson et al., 2007; Zhao et al., 2011), whereas the N2pc amplitude was not affected. That is, the allocation of selective attention toward the change was delayed with a larger number of irrelevant stimuli. Obviously, attention was attracted by the distractors before it was shifted to the relevant change (cf. Mazza et al., 2009).

Second, we hypothesized that top-down mechanisms that determine the way how observers search for the change are mirrored by the N2pc amplitude only (Eimer, 1996). Our results show that the N2pc amplitude was enhanced when change positions were permanently highlighted. Interestingly, also the peak latency of the N2pc appeared earlier. This finding can be compared to a study that manipulated top-down activity by varying the instructions of a task (Gazzaley, Cooney, McEvoy, Knight, & D'Esposito, 2005). Participants had to remember and / or ignore pictures of sequentially presented faces and / or scenes. The N170 in the ERP was measured, reflecting the attentional processing of faces. The results show that the amplitude of the N170 was enhanced and the latency was preponed when observers had to remember faces compared to when they had to ignore faces. Similar to our findings, top-down activity affected both the magnitude and the speed of attention. A greater magnitude of attention allows amplifying the neural information which can be gathered from the relevant stimulus (cf. Gazzaley et al., 2005; Hillyard, Vogel, & Luck, 1998). The speed of attention, which is influenced by task demands, mirrors processing speed that further enhances the neural efficiency and thus also the probability that relevant information can be successfully represented in memory (Gazzaley et al., 2005). Therefore, we suggest that also in change blindness, top-down activity influences the perceptual competition of the stimuli for further processing and thus alleviating ongoing memory encoding a) by enhancing the magnitude of attention that is allocated onto the change and b) by increasing the processing speed of attention.

One may argue that the top-down manipulation may be a mixture of top-down and bottom-up activity in the present study. When change positions were permanently highlighted in red color, participants were asked to detect luminance changes from light red to dark red or vice versa. In all remaining conditions, however, observers should detect luminance changes from light gray to dark gray or vice versa. There is a small probability that the luminance of gray changes differed from that of red changes. This might have incorporated additional bottom-up processes. Thus, for future studies we suggest to manipulate top-down activity not by varying the characteristics of the stimuli, but for example by instructing participants differently. To investigate the interplay between bottom-up and top-down mechanisms (Folk et al., 1992; Müller & Rabbitt, 1989) it would be interesting to simultaneously vary the number of mudsplashes and highlight potential change positions in one experimental condition. Together, the results point to the competitive function of visual attention in change blindness that is based on two different mechanisms: First, bottom-up processes delay the allocation of attention onto the changes. Second, top-down delay the allocation of attention and, in addition, reduce the effort which is necessary to detect changes.

Interestingly, an N2pc was present for detected changes only. This contradicts former studies (Schankin, Hagemann, & Wascher, 2009; Schankin & Wascher, 2007, 2008) who observed an N2pc for detected changes and an N2pc of smaller amplitude also for undetected changes with a nearly identical change blindness paradigm. We suggest that this deviant finding might be due to a different sample composition with a lower average age, mainly students in the studies by Schankin and colleagues. In contrast, in the present study an older community sample was recruited via newspaper advertisement and web portals.

Limitations

Before strong conclusions might be drawn, some further limitations of the current experiment have to be considered. First, Eimer and Mazza (2005) reported that the N2pc latency was related to how fast observers detected the change. They proposed that RTs should be measured to control for these effect. In the current study, however, reaction times were nor related to the N2pc onset latency (LOW-NUMBER-OF-MUDSPLASHES condition, $r = .043$, $p = .819$; HIGH-NUMBER-OF-MUDSPLASHES condition, $r = .093$, $p = .618$; NOT-HIGHLIGHTED condition, $r = .212$, $p = .252$; HIGHLIGHTED condition, $r = .167$, $p = .370$) nor to the N2pc peak latency (LOW-NUMBER-OF-MUDSPLASHES condition, $r = -.142$, $p = .447$; HIGH-NUMBER-OF-MUDSPLASHES condition, $r = .098$, $p = .618$; NOT-HIGHLIGHTED condition, $r = .213$, $p = .251$; HIGHLIGHTED condition, $r = .134$, $p = .471$).

Second, not only participants' sensitivity for changes, but also their response behavior varied between experimental conditions. In particular, observers responded more conservatively with an enhanced number of mudsplashes and when change positions were not highlighted compared to highlighted positions. This observation is in line with former research that indicated that conservative response behavior increased with task demands (cf.

Woodward, Meier, Tipper, & Graf, 2003). In the present study, however, the sensitivity for changes was not related to participants' response behavior. Nevertheless, response behavior could have affected magnitude and speed of attention. Thus, the relationship between the allocation of attention and response bias in change blindness needs to be examined in future research by keeping participants' sensitivity for changes constant and varying only their response behavior.

Conclusion

Despite these limitations, the results of the current study show that the allocation of attention in change detection and change blindness and thus the probability to detect a change depends on the relationship between the changing object and other visual disturbances as well as the relationship between the changing object and other non-changing objects. Irrelevant distractors perturb the allocation of attention to the change (bottom-up). Electrophysiologically, this mechanism is reflected by the latency of the N2pc component. How attention is intentionally focused to potentially changing objects (top-down) is reflected by the amplitude peak latency of the N2pc. That is, bottom-up mechanisms are fast and mainly affect the speed of attentional allocation, whereas top-down mechanisms mainly affect the magnitude of attention, which is allocated onto the change in a change detection task. Thus, successful change detection depends on the properties of distracting as well as non-changing objects, which both determine the speed and intensity of the allocation of attention toward a change.

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Ethical Standards

All human studies have been approved by the appropriate ethics committee and have therefore been performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and its later amendments. All persons gave their informed consent prior to their inclusion in the study. Details that might disclose the identity of the subjects under study were omitted. The manuscript does not contain clinical studies or patient data.

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Ethical Standards

All human studies have been approved by the appropriate ethics committee and have therefore been performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and its later amendments. All persons gave their informed consent prior to their inclusion in the study. Details that might disclose the identity of the subjects under study were omitted. The manuscript does not contain clinical studies or patient data.

Tables

Table 1. Overview of the different experimental analyses (bottom-up and top-down) and the conditions (LOW-NUMBER-OF-MUDSPLASHES, HIGH-NUMBER-OF-MUDSPLASHES, NOT-HIGHLIGHTED, HIGHLIGHTED). Mean accuracy rates in percentage, mean N2pc latency (onset and peak), and mean N2pc amplitude (*SEM* = standard error of mean) as a function of condition.

Analysis	**Condition**	**Muds.**	**High.**	**Luminance Changes (*SEM*)**	**No Changes (*SEM*)**	**Onset Latency (*SEM*)**	**Peak Latency (*SEM*)**	**Amplitude (*SEM*)**
Bottom-Up	LOW-NUMBER-OF-MUDSPLASHES	4	No	43.5 (3.4)	95.0 (1.1)	208.0 (.3)	326.2 (.3)	-1.2 (.2)
Bottom-Up	HIGH-NUMBER-OF-MUDSPLASHES	8	No	30.7 (2.8)	93.7 (1.1)	317.7 (1.6)	367.6 (.3)	-1.4 (.5)
Top-Down	NOT-HIGHLIGHTED	6	No	35.8 (2.8)	90.0 (1.9)	223.3 (.5)	333.5 (.2)	-1.4 (.2)
Top-Down	HIGHLIGHTED	6	Yes	87.5 (1.9)	96.7 (.8)	231.2 (.1)	302.3 (.1)	-2.1 (.3)

Note. Muds. = Number of Mudsplashes; High. = Highlighted change positions.

Figures

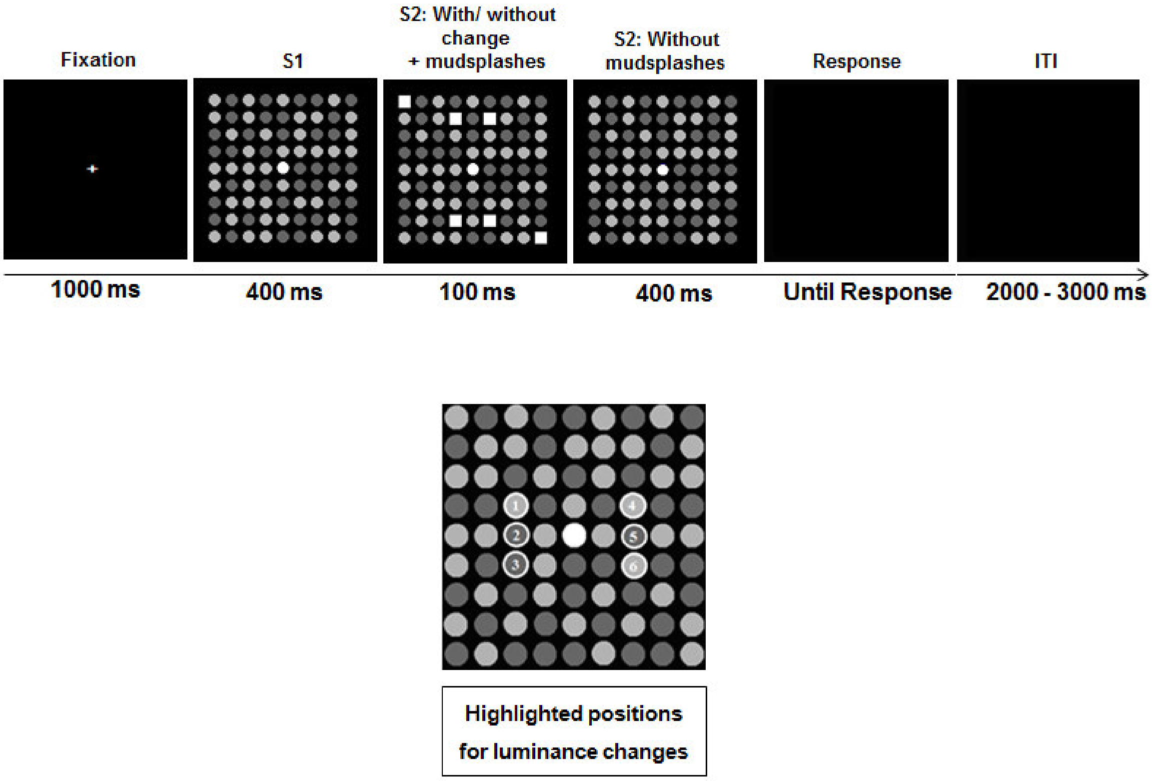

Figure 1. Example for an experimental trial. After a fixation cross (1000ms), matrix S1 appeared (400 ms), then matrix S2 with a possible change (lateral luminance or central color change) followed (100 ms), simultaneously with the mudsplashes. Subsequently, S2 remained on the screen for another 400 ms without the mudsplashes. Afterwards, participants indicated whether they had seen a change or not. Finally an inter-trial interval (ITI) of 2000 – 3000 ms appeared. In this example, six mudsplashes were presented as in the NOT-HIGHLIGHTED block and in the HIGHLIGHTED block. In the NUMBER-OF-MUDSPLASHES block, four or eight mudsplashes appeared in intermingled sequence. The dot in the center of the matrix was colored in either red or green. In the matrix below, the six possible luminance change positions are marked in white color (not visible in the experiment). In Block 3 these positions were permanently marked in red color.

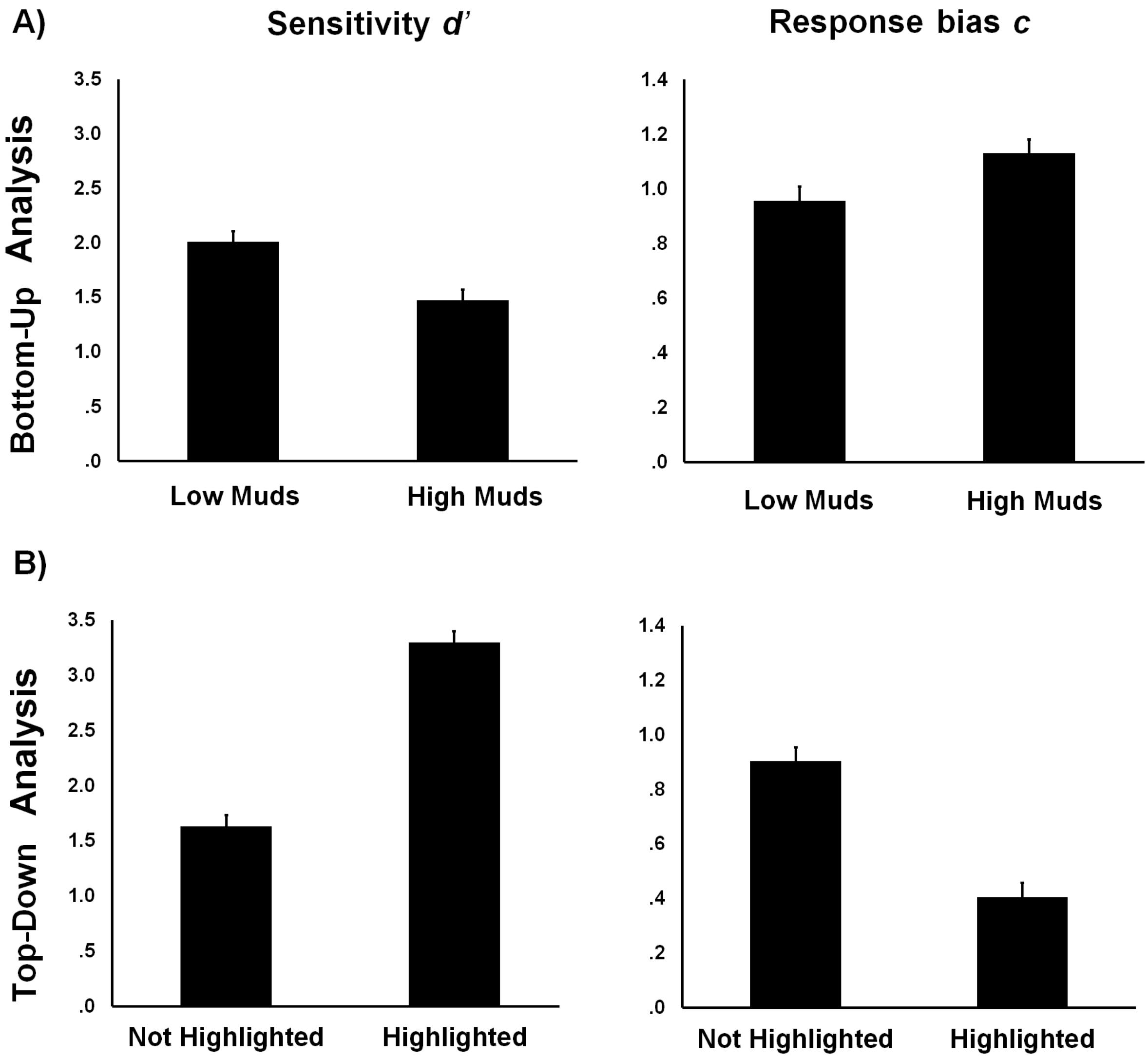

Figure 2. Mean values and standard errors of behavioral data for sensitivity *d*' (A) and response bias *c* (B) for the bottom-up analysis and the top-down analysis; LOW-NUMBER-OF-MUDSPLASHES (Low Muds); HIGH-NUMBER-OF-MUDSPLASHES (High Muds).

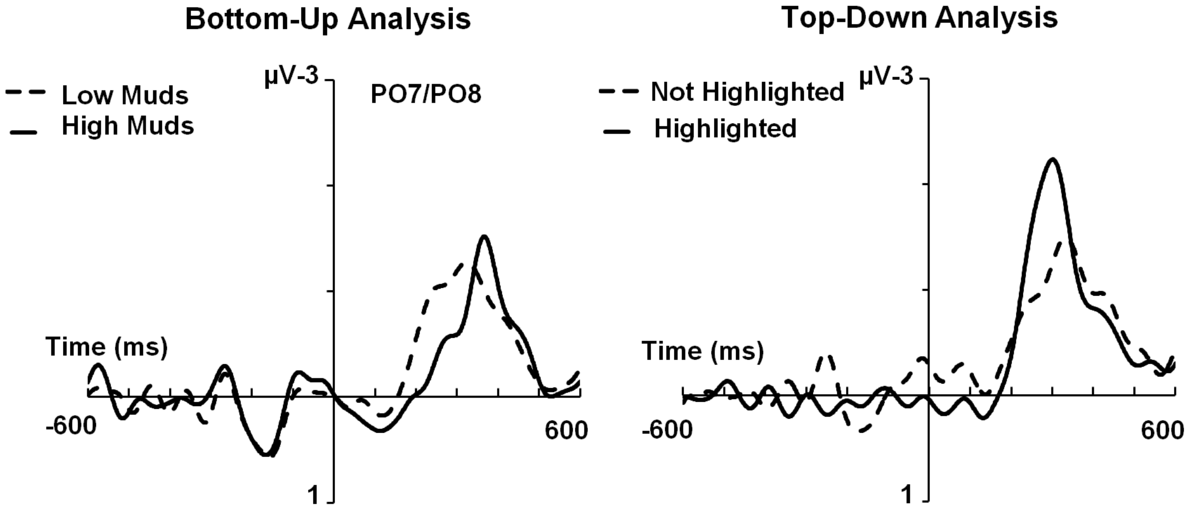

Figure 3. Difference waveforms. The N2pc for detected changes was extracted from the ERP by subtracting the ispilateral from the contralateral activity evoked by the onset of the change. The bottom-up analysis shows the difference waveforms of the LOW-NUMBER-OF-MUDSPLASHES condition (Low Muds) and the HIGH-NUMBER-OF-MUDSPLASHES condition (High Muds). The top-down analysis shows the difference waveforms of the NOT-HIGHLIGHTED condition and the HIGHLIGHTED condition.

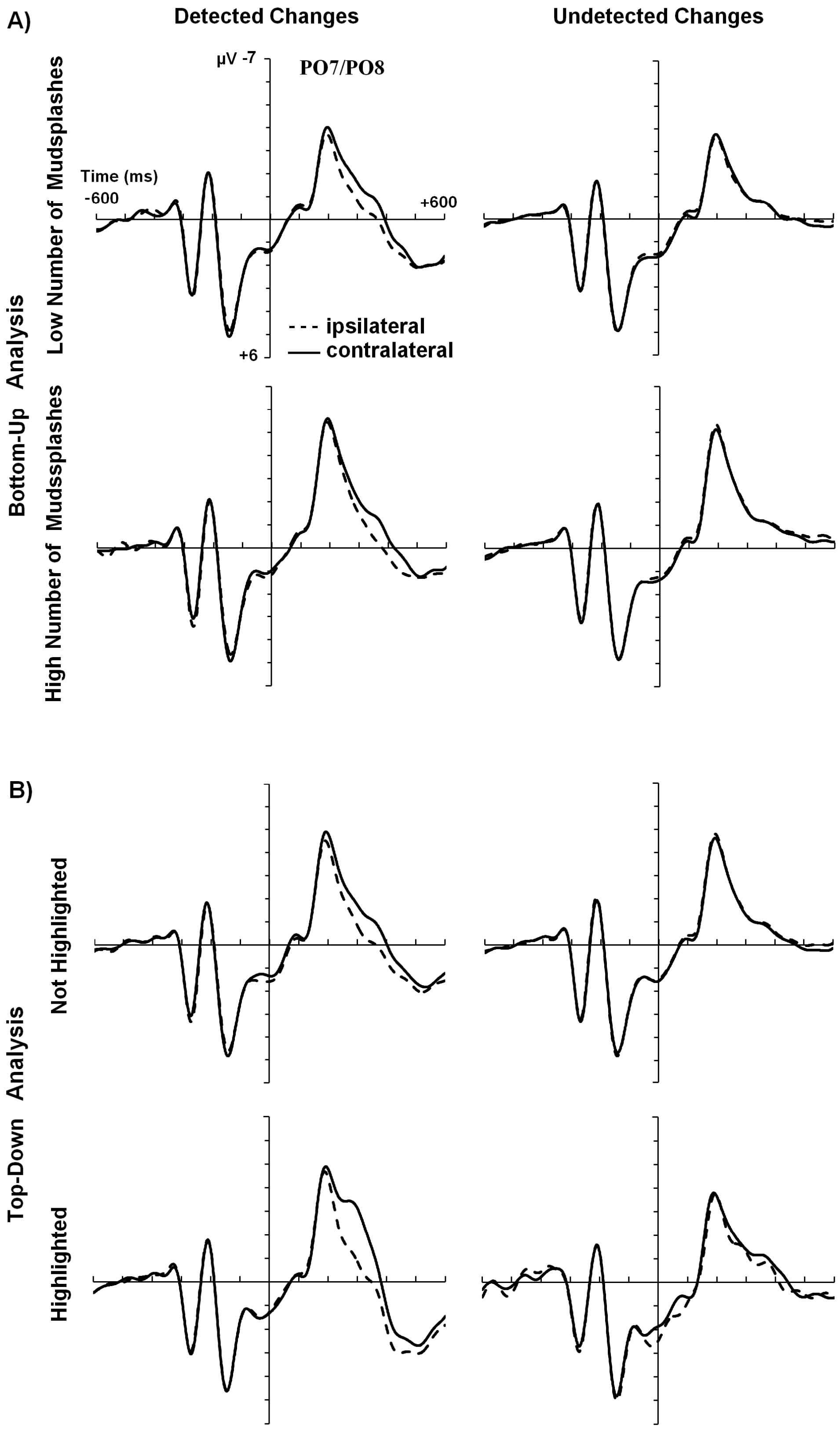

Figure 4. Grand-averaged ERP waveforms separately for detected changes and for undetected changes, evoked by the change at posterior electrodes (PO7/PO8) contralateral (solid line) and ipsilateral (dashed line) to the change location.

Appendix A2 - manuscript 2

INTERINDIVIDUAL DIFFERENCES IN CHANGE DETECTION AND CHANGE BLINDNESS

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Abstract

Observers often miss visual changes in the environment when they co-occur with other visual disruptions. This phenomenon is called change blindness. The first aim of the current study was to investigate whether individual differences in change blindness are due to a trait. The second aim was to assess which neurocognitive processes contributed to these individual differences. Participants performed a change detection task at three measurement occasions. The N2pc was measured as an indicator of the allocation of attention and the P3 amplitude as an indicator of post-perceptual processes. For data analysis, we applied latent state-trait models. The results suggest that the sensitivity for changes is a consistent and valid personality trait. This finding has a high practical relevance, e.g. for the design of adaptive visual environments. Distinct processes explain these individual differences in change blindness. Both attentional mechanisms and post-perceptual processes contribute to and amplify the individual sensitivity for changes.

Keywords: Change blindness, Individual Differences, Latent State-Trait-Models, Selective Visual Attention, Post-Perceptual Processes, N2pc, P3

Inter-individual differences in change detection and change blindness

What makes a soccer goalkeeper one of the best of his profession? Among other prerequisites, e.g. motoric skills, he or she has to possess the ability to stay focused and to detect even slight changes in the environment. It is known that persons differ in their goal-keeping performance. Does this imply that a professional goal keeper's excellent ability to detect changes is consistent across time, different situations, and methods, i.e. is change detection a latent trait (cf. McAdams, 1994, 1995; McCrae & Costa, 2003; Steyer et al., 1992).

Change blindness

Like the goalkeeper, observers do not perceive all details of our visual environment, like objects, scenes or motion pictures from one view to the next (e.g., Simons, 2000). It is possible that they miss changes in a visual scene when the transient motion signal of the change that normally attracts observers' attention automatically is simultaneously perturbed by some other signals. This phenomenon is known as change blindness (e.g., Simons & Levin, 1997). In an experimental setting, the motion signal of the change can be interrupted, e.g. by the presentation of a short blank (e.g., Rensink et al., 1997), by the presentation of mudsplashes (e.g., Schankin & Wascher, 2007, 2008; O'Regan et al., 1999), or by a film-cut (e.g., Levin & Simons, 1997; Simons, 1996), but the phenomenon may even occur in in real-life interactions (Simons & Levin, 1998).

Asked for their own ability to detect changes, the majority of people are convinced to perform well in change detection (Levin et al., 2000). For example, it seems to be common to use a mobile phone while driving because people overestimate their ability to watch the traffic attentively while they are simultaneously distracted by talking to someone else (cf. Simons & Ambinder, 2005). In contrast to common believes, a surprisingly large percentage of observers do not detect visual changes (e.g., Levin & Simons, 1997; Levin et al., 2002; Simons & Levin, 1998). For example, real-life experiments show that about 50% of naive participants did not notice the exchange of their conversation partner when a door, carried by construction workers, separated participant and experimenter from each other (Simons & Levin, 1998) or when the participant was taking a photograph of the experimenter (Levin et al., 2002; Davies & Hine, 2007). Application-oriented research reveals similar results. For example, in an eyewitness task 35% of the participants who watched videos of a house burglary did not realize that the person who was acting the burglar was replaced by a different actor (Davies & Hine, 2007). The metacognitive error that people extremely overrate their own and others sensitivity to detect even highly salient changes has been named *change blindness blindness,* i.e. observers' unability to correctly estimate their own extent of change blindness (Levin et al., 2000). With reference to this, it is not possible to simply assess observers' sensitivity for changes by asking them, because they are not able to evaluate themselves properly. Some observers are able to detect changes, whereas a great percentage is change blind. Therefore, research on individual differences in change blindness has a great practical relevance. It is important to know why persons are change blind, whereas others seem to detect changes easily, e.g., in driving, navigation, surveillance, or eyewitness testimony (cf. O'Regan et al., 1999; Simons & Levin, 1998).

There are several examples for individual differences in change blindness. They are associated with long-term patterns of behavior or expertise (e.g., Jones, Jones, Smith, & Copley, 2003; Werner & Thies, 2000), by dependence on group membership (e.g., Simons & Levin, 1998), by dispositional anxiety (e.g, McGlynn et al., 2008), by age (e.g., Caird et al., 2005), or by cultural background (e.g., Humphreys et al., 2005; Masuda & Nisbett, 2006). For example, one study analyzed different change types as a function of expertise in American football (Werner & Thies, 2000). Participants were asked to detect changes in action scenes and scenes of playing formations. Two types of changes could occur, either semantic changes with meaningful information (e.g., the exchange of an important football player in the scene) or non-semantic changes without meaningful information (e.g., a color change). Traffic-related scenes were used as control scenarios. Football experts were more sensitive to changes of domain-related, semantic photographs than novices, whereas for the control scenes no such effect of context was found. Similarly, also cultural differences became visible in change detection performance (Masuda & Nisbett, 2006). Japanese or American observers had to detect contextual changes presented in the background (e.g., a change of the position of clouds) or focal changes presented in the foreground of photographs or movie films. Japanese were more sensitive to contextual changes, whereas Americans' performance was better for focal changes.

These studies show that individual differences in change blindness exist. They have been assessed in different experimental settings and across different situations. However, it is unclear whether individual differences in change blindness reflect a trait-like characteristic, i.e. whether a person is able to detect changes better than others, independently of situation and measurement method. Alternatively, change detection might simply rely on situational effects. That is, observers' sensitivity for changes may, for example, differ from day to day, due to motivation or fatigue or it may be specific for certain situations. Moreover, methodological effects might play a role in change detection. For example, the presentation of a short blank (e.g., Rensink et al., 1997, 2000) or the presentation of mudsplashes (e.g., O'Regan et al., 1999) both reduce the transient motion signal of the change, but with a different degree of change blindness. Finally, unsystematic measurement errors contribute to unintended variance in change blindness, e.g., when observers accidentally make mistakes. A possible consequence of this is a low reliability of observers' sensitivity for changes. An attempt to systematically integrate these findings and to find a consistent explanation for these findings has not been made yet. It is still unclear if change blindness is a trait, which is independent from the situation and the measurement method. Therefore, it is necessary to separate confounding effects of the person, the situation and the method on change detection performance.

Latent state trait models

The effects of the person, the situation, the method, and the measurement error on the performance measure can be estimated and separated with the help of structural equation models. In particular, the latent state-trait (LST) theory takes into account that not only persons, but also situations and the interaction between persons and situations are important sources of variance in psychological measurement (Hagemann & Meyerhoff, 2008; Steyer et al., 1999). The core of LST models is based on two main variance decompositions: First, the variances of the observed variables can be decomposed into the variances of the latent states and of the measurement errors. And second, the variances of the latent state components can be decomposed into the variances of the latent state residuals and of a latent trait. For the separation of trait effects from situational effects several repeated measurements are necessary. Additional, so-called latent method factors can be included into the model. These factors indicate the proportion of variance that is due to the application of different methods. Unlike manifest variables, latent variables have the advantage that they measure error-free variables and measurement errors can be controlled (cf. Bollen, 1989).

The aim of the present study is to investigate whether change blindness is a trait by estimating its trait specific variance. Apart from this, it is important to investigate which processes underlie individual differences in change blindness. Past research indicated that both attentional change processing (e.g., Rensink et al., 1997) and post-perceptual change processing (e.g., Koivisto & Revonsuo, 2003) play a major role in change detection and change blindness.

Selective attention

Visual attention is the core mechanism of the selective processing of visual objects and events in the environment. It helps to resolve the competition of these stimuli for preferred processing by selecting salient or relevant stimuli while ignoring irrelevant, unimportant ones. For successful change detection, selective attention is necessary (e.g., Rensink et al., 1997; Schankin & Wascher, 2008; Simons, 2000). For example, past research indicated that only stimuli in the focus of attention can be reported consciously, as measured with eye-tracking (e.g., O'Regan et al., 2000). Furthermore, when attention is directed to a change location by a cue presented before the occurrence of a change, change blindness is prevented (Lamme, 2003). It was suggested that attentional processing is associated with individual differences in change blindness. For example, change blindness may result from capacity limitations of attention (e.g., Masuda & Nisbett, 2006; Simons & Ambinder, 2005; Cowan, 2000). Individual differences, e.g. in dipositional anxiety, also guide the focus of attention and influence the way how changes are seen and encoded (McGlynn et al., 2008).

One component of the event-related potential (ERP) that is sensitive to the attentional selection of visual stimuli, is the N2pc. The N2pc is a difference wave, which occurs about 200 to 300 ms after stimulus onset contralateral to the stimulus location at posterior electrodes. It indicates the allocation of observers' selective attention (Eimer, 1996; Luck & Hillyard, 1994a, 1994b; Woodman & Luck, 1999). Some findings showed individual differences in the size of the N2pc amplitude that reflected systematic differences in self-esteem (H. Li et al., 2012) or anxiety (Fox et al., 2008) in spatial cueing tasks.

In a majority of change detection tasks, an N2pc is evoked by stimuli that reached visual awareness, e.g. when participants reported changes in face expressions (Eimer & Mazza, 2005), in meaningful objects (Busch, Dürschmid, et al., 2010; Busch, Fründ, et al., 2010), or in colored dots (Schankin & Wascher, 2007). Sometimes, an N2pc with a smaller amplitude was also found for undetected changes (Schankin & Wascher, 2007, 2008; Schankin et al., 2009). In the current study, the amplitude of the N2pc component is used as an indicator of selective attention. If individual differences in change detection rely on differences in attentional selection, this should be reflected by the N2pc amplitude.

Post-perceptual processing

In addition to rather early processing that is indicated by the N2pc some post-perceptual change processing is necessary for ongoing decision making and action planning (e.g., Koivisto & Revonsuo, 2003). This processing in a later phase of conscious change evaluation may contribute to individual differences in change blindness. Post-perceptual cognitive processes are reflected by relatively late ERP components, such as the P3. This component is a large positive peak about 300 ms after stimulus onset with maximal amplitude at parietal and central midline scalp sites. It has first been described by Sutton et al. (1965) as a reaction to an unexpected event. Context or working memory updating is the most common interpretation of its meaning (e.g., Donchin & Coles, 1988; Verleger, 1988). There is some evidence for individual differences in the P3 amplitude (Polich & Kok, 1995; Polich, 2007). For example, in a variety of visual tasks the size of the P3 amplitude depended on participants’ extraversion (e.g., Brocke et al., 1997; Daruna et al., 1985; Stenberg, 1994) or on participants’ age (e.g., Fjell & Walhovd, 2003, 2004, 2005; D. Friedman, 2008).

Several studies have shown that successful change detection is mirrored by an enhanced P300 or P3 component (e.g., Koivisto & Revonsuo, 2003; Niedeggen et al., 2001; Turatto et al., 2002). In particular,Koivisto and Revonsuo (2003) suggested that the difference between detected changes and undetected changes in the P3 amplitude reflects post-perceptual processes of conscious change evaluation, e.g. the P3 may indicate a process which is necessary for ongoing decision making. Similarly, in a study by O'Connell et al. (2012), the ERP showed a single, centro-parietal positivity, which was elicited by the gradual onset of a change. This positivity grew in amplitude with accumulating sensory evidence and peaked simultaneously with participants’ response. The authors conclude that this positivity equals the P3 component and mirrors a goal-oriented decision process, determined by threshold-bound accumulation of perceptual evidence. It was suggested that the starting level of the perceptual accumulation process might vary as a function of individual differences (O'Connell et al., 2012).

The present study

Research on individual differences in change blindness has a high practical relevance, e.g. for car driving or eyewitness testimonies. Why are some persons change blind, whereas others perform well in change detection tasks? The first aim of the present study was to investigate whether the ability to detect changes in the visual environment is a trait, i.e. a variable that is stable across time, different situations, and methods (e.g., McCrae & Costa, 2003; Steyer et al., 1992). This question was assessed by applying the ideas of LST models (cf. Steyer et al., 1999). Therefore, change detection performance was measured at three measurement occasions with four different methods in order to assess the portion of variance that is attributable to the trait, situations, methods, and errors. If the sensitivity for changes were a trait a high proportion of variance would be explained by a latent trait variable in the LST model, whereas the effects of methods, situations, and measurement errors should be low. Furthermore, the convergent and discriminant validity of individual differences in the sensitivity for changes should be evaluated with respect to standard measures of personality and intelligence.

A second aim of the current study was to explore which cognitive processes might be associated with individual differences in change detection and change blindness. Two processes are of interest here, selective attention and post-perceptual processes. In the current study we used abstract dot patterns to measure the event-related brain activity. If selective attention or post-perceptual change processing were underlying mechanisms of the ability to detect changes, this should be reflected by individual differences in the N2pc or the P3 component of the ERP, respectively.

Methods

Participants

Sixty paid (8€/hour) volunteers (33 women, 27 men, aged between 18 and 73, mean age 40.5 years) from a community sample participated in the experiment. Participants were recruited via newspaper advertisement and web portals. Five participants were left-handed, 54 were right-handed and one of them was bimanual. When asked for their educational background, one participant indicated to have finished a degree of German lower secondary school, six participants had an intermediate school leaving certificate, seven a vocational diploma, 18 a college degree, 24 a university degree and four a degree of doctorate. Four participants were unemployed, two attended school, eight were students, 29 employees, twelve freelancers, and five retired. Before the experiment started, participants were informed that it was required that they were not under psychiatric or neurological treatment. Participants reported normal or corrected to-normal vision and had normal color vision as measured with the Ishihara test of color blindness. All of them gave their written informed consent. The study was carried out in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and its amendments.

Measurement Occasions

Overall, four measurement occasions were conducted. A mean of 15 weeks passed between measurement occasion one and two, a mean of 14 weeks between measurement occasion two and three, and a mean of four weeks between measurement occasion three and four. At measurement occasion one to three behavioral and electrophysiological data were recorded while the change blindness task was conducted. At measurement occasion four further measures were collected to assess the validity of the change blindness measures.

Apparatus & Stimuli

Participants were individually tested in a comfortable chair in a sound-attenuated chamber, which was dimly lit and electrically shielded. Two keys on a keyboard served as response buttons. The left key was marked in red and the right key in green color. They were located under participants' left and right index finger. Stimuli were presented on a 17-in. computer screen, placed 82 cm in front of them, at the center of their field of vision. The screen was set to a resolution of 1280 x 1024 pixels and a screen refresh rate of 60 Hz.

Stimuli consisted of 81 dots which were arranged in a 9 x 9 matrix (3.42° x 3.42° of visual angle) and presented on a black background (L = 0, a = 0, b = 0 in L*a*b color space). Forty of the dots were colored light gray (L = 73, a = 0, b = 0), 40 dots were colored dark gray (L = 42, a = 0, b = 0), and the dot in the center of the matrix was colored either green (L = 34, a = -38, b = 39) or blue (L = 34, a = 58, b = -105). The distance between single dots was .10° and their diameter .28°. The positions of the light and dark gray dots in the matrix were balanced so that accumulations of dots with equal luminance were avoided (cf. Figure 1). In this way, nine matrices were created, which were used for all experimental conditions equally often. In the BLOCK 3 light red (L = 73, a = 38, b = 42) and dark red (L = 42, a = 61, b = 55) dots replaced six of the gray dots (cf. Figure 1).

White squares (L = 100, a = 0, b = 0) served as *mudsplashes*. The number of mudsplashes (four, six, or eight) varied between conditions. Each mudsplash (.28° x .28°) occluded exactly one gray dot. The mudsplashes never appeared in immediate vicinity to each other or to a change location. Half of the mudsplashes were presented to the left and half to the right visual hemifield. Relative to their distance to the center, they were always presented symmetrically, mirrored along the vertical axis. Fifteen possible arrangements of their spatial positions were constructed in advance and then quasi-randomly ordered per block so that the same arrangement of mudsplashes never appeared more than three times consecutively.

Procedure

Each trial began with a fixation cross in the center of the screen, which lasted 1,000 ms (cf. Figure 1). Then, the first matrix (S1) appeared for 400 ms. Subsequently, the second matrix (S2) was presented for 100 ms, simultaneously with the mudsplashes. Then, the mudsplashes disappeared and the matrix remained on the screen for another 400 ms. On about 43% of the trials, S1 and S2 were identical (no change trial), on about 43% of the trials, one lateral dot changed its luminance at one of six possible locations (luminance change trial), and on about 14% of all trials, the colored dot in the center changed its color (color change trial). Color changes were used to keep participants' attention fixed to the center of the screen and were excluded from further analyses because in this condition no change blindness effect can be observed (cf. Schankin & Wascher, 2008). Figure 1 shows the three dots of position 1, 2, and 3, (left hemifield) and the three dots of position 4, 5, and 6 (right hemifield). On half of the luminance change trials, the dot changed from dark gray to light gray, on the other half from light gray to dark gray. Similarly, on half of the color change trials, the central dot changed from green to blue, on the other half from blue to green. Finally, an inter-trial interval (ITI) of variable length (2,000 – 3,000 ms) followed.

Participants were instructed to indicate if they had seen a change or not by pressing the green or red key, respectively. The assignment of response keys was counterbalanced across participants. It was stressed that they should report a change only when they really saw it, and that guessing was not allowed.

There were four experimental conditions (cf. Table 1). First, in the LOW-NUMBER-OF-MUDSPLASHES condition, four mudsplashes were presented. Second, in the HIGH-NUMBER-OF-MUDSPLASHES condition, eight mudsplashes were shown. Third, in the NOT-HIGHLIGHTED

CONDITION, six mudsplashes were presented. Fourth, in the HIGHLIGHTED condition, also six mudsplashes were presented and in addition, the six possible positions of luminance changes were permanently marked in red color.

These four experimental conditions were presented in three blocks. In BLOCK 1, either four (LOW-NUMBER-OF-MUDSPLASHES condition) or eight mudsplashes (HIGH-NUMBER-OF-MUDSPLASHES condition) were presented simultaneously with the change. In BLOCK 2, only the NOT-HIGHLIGHTED condition was presented. In BLOCK 3, only the NOT-HIGHLIGHTED condition was shown. The NOT-HIGHLIGHTED and HIGHLIGHTED conditions were presented in separate blocks to avoid interference effects by the highlighted change positions on consecutive trials. This separation, however, was not considered necessary for the LOW- and HIGH-NUMBER-OF-MUDSPLASHES conditions, which were presented in one block. Within a block, all trials were shown in random sequence with the following constraints. At maximum three luminance changes, three no changes, three changes of the same (left or right) side or two color changes appeared successively. Furthermore, the same matrix never appeared more than three times consecutively. In this way, four different trial sequences were created for each block and systematically assigned to participants. Short breaks of individual length always appeared after about seven minutes. After each block, there was a longer break.

Overall, three measurement occasions were performed. On each measurement occasion, the experiment started with a short demonstration of all possible changes. On each change position, one exemplary change appeared in slowed presentation time and without any mudsplashes to ensure that all possible changes had been seen once by the participants. Then participants passed a short exercise of 91 trials (42 luminance changes, 42 no changes and seven color changes). In the exercise, six mudsplashes were presented. The procedure of a trial was the same as described above, six mudsplashes were presented as distractors. To prevent sequence effects, the sequential presentation of the experimental blocks was varied per measurement occasion. At measurement occasion one, the exercise was followed by BLOCK 2, then by BLOCK 1 and finally by the BLOCK 3. On the second measurement occasion, first BLOCK 3 was presented, then BLOCK 2 and finally BLOCK 1. Measurement occasion three started with BLOCK 1, followed by the BLOCK 3 and then by BLOCK 2.

Each of the four experimental conditions consisted of 9 (matrices) x [4 (color changes) + 12 (luminance changes) + 12 (no changes)] x 3 (measurement occasions) = 756 trials with

316 luminance changes, 316 no changes and 108 color changes each. Altogether, this resulted in 3024 trials per participant.

EEG Recording

EEG was continuously recorded from 25 Ag-AgCl electrodes, placed according to the international 10–20 system. During recording, all electrodes (F3, Fz, F4, T7, C3, C4, T8, Tp9, Tp10, P7, P3, Pz, P4, P8, PO7, PO8, O1, Oz, O2) were referenced to Cz. Fpz was used as ground. Vertical electro-oculogram (EOG) was recorded bipolarly from above and below the right eye and horizontal EOG from the outer canthi of the eyes. Electrode impedances were kept below 5 kΩ. EEG was sampled with a rate of 1000 Hz. The signal was amplified by two BrainAmp DC amplifiers (Brain Products, Munich, Germany) with a band-pass of 0.1 - 250 Hz. Data was filtered off-line with a band-pass filter of 0.1 – 12 Hz and re-referenced to linked mastoids. EEG data were segmented into time windows of 1,700 ms, starting 200 ms prior to S1 and ending 1,400 ms afterward. Baseline was corrected relative to the activity of the interval 200 ms prior to S1 to 0 ms (-600 to -400 ms prior to S2). Ocular artifacts were corrected according to the algorithm of Gratton et al. (1983). Trials with amplitudes lower than .5 µV in an interval of 100 ms, exceeding +/- 70 µV, or with a voltage step of 100 µV/ms were excluded from the data as artifacts.

Data Analysis

Behavioral data. *Hits* (percentage of correctly detected luminance changes) and *false alarms* (percentage of reported changes in no change trials) were computed separately for each of the four experimental conditions and the three measurement occasions. To distinguish between effects due to sensitivity and response bias, sensitivity *d*' and response bias *c* were calculated according to the signal detection theory (Green & Swets, 1966). To investigate whether the sensitivity for changes or the response bias differed between conditions four repeated-measures ANOVAs were calculated with the within-subjects factor condition (a): LOW- VS. HIGH-NUMBER-OF-MUDSPLASHES condition[1] (manipulation of the number of mudsplashes) or (b) HIGHLIGHTED VS. NOT-HIGHLIGHTED condition (manipulation of highlighted change positions), separately for *d*' and *c*.

Latent state-trait model of sensitivity d'. We applied an LST model for sensitivity *d'* in order to test the hypothesis whether the sensitivity for changes is based on a trait, which is stable across different situations and methods (cf. Steyer et al., 1999). Four manifest variables (low- and high-number-of-mudsplashes, highlighted and not-highlighted change positions) were set up at three different measurement occasions. Following the recommendation of Eid (2000), a M-1 model allows a LST model with only three method factors (i.e., LOW- and HIGH-NUMBER-OF-MUDSPLASHES and HIGHLIGHTED condition) to assess that portion of variance caused by different measurement methods. The NOT-HIGHLIGHTED conditions was used as a baseline, i.e. a reference condition, for the following reasons: First, the NOT-HIGHLIGHTED condition (six mudsplashes) served as a neutral condition to the LOW-NUMBER-OF-MUDSPLASHES condition (four mudsplashes) and the HIGH-NUMBER-OF-MUDSPLASHES condition (eight mudsplashes). Second, the NOT-HIGLIGHTED condition served as a comparison condition to the HIGHLIGHTED condition, which both included the presentation of six mudsplashes and differed only with respect to (not) highlighted change positions. Thus, the NOT-HIGHLIGHTED condition can be regarded as the most neutral reference condition in the current experimental design.

The LST model was fitted by minimalizing the generalized least squares discrepancy function (GLS; Hu & Bentler, 1998), implemented in AMOS 20.0 (Arbuckle, 2006). The general model fit was evaluated by indices of the χ^2 statistics, the comparative fit index (CFI; Bentler, 1990) and the root mean square error of approximation (RMSEA; Browne & Cudeck, 1992). The critical ratio was used to assess the significance ($p \leq .05$) of the single model parameters.

Next, the portion of variances of the manifest variables that are determined by their latent components were analyzed with the help of standard LST parameters, based on the estimated parameters (for formulae, see Deinzer et al., 1995; Steyer et al., 1992). A *coefficient of trait specifity* shows the portion of variance that is due to the latent trait. A *coefficient of occasion specifity* reflects the portion of variance of the manifest variable that is due to the influence of the measurement occasion (situation) or the interaction of the situation and the person. Finally, a *coefficient of method specifity* describes that portion of variance of the manifest variable that is due to the influence of the method or to the interaction of the method and the person. The closer the value of these parameters is to 1, the greater the specifity. Finally, a *coefficient of reliability* describes the error-free portion of variance of the latent components.

Electrophysiological data. The N2pc was extracted from the ERP by subtracting the activity ipsilateral from those contralateral relative to the position of a change. The amplitude was measured as the mean activity at posterior electrodes (cf. Eimer, 1996; Luck & Hillyard, 1994a; Schankin & Wascher, 2007, 2008) in different time windows after change onset, because its maximum varied between conditions: LOW-NUMBER-OF-MUDSPLASHES: 290 to 340 ms, HIGH-NUMBER-OF-MUDSPLASHES: 340 to 390 ms; NOT HIGHLIGHTED change positions: 310 to 360 ms, HIGHLIGHTED change positions: 280 to 330 ms. Data from PO7/PO8 were entered into further statistical analyses because the N2pc was maximal at these electrode positions. To test if the N2pc amplitude was elicited by detected changes and by undetected changes, t-tests were calculated, separately for the experimental conditions (LOW-NUMBER-OF-MUDSPLASHES condition, HIGH-NUMBER-OF-MUDSPLASHES condition, NOT-HIGHLIGHTED condition, HIGHLIGHTED condition)

The P3 amplitude was maximal about 500 ms after change onset (S2) in all conditions. For statistical analyses, the P3 amplitude was measured as mean activity in the time window from 400 to 600 ms after change onset. Data from Pz were entered into further analyses because the P3 was maximal at this electrode position. This observation is in accordance with other studies that found maximal P3 amplitude sizes for posterior electrode sides (D. Friedman, Kazmerski, & Fabiani, 1997b; Polich & Heine, 1996). To test whether the P3 amplitude is increased for detected changes in comparison to undetected changes, as suggested by Koivisto and Revonsuo (2003), t-tests were calculated, separately for the experimental conditions (LOW-NUMBER-OF-MUDSPLASHES condition, HIGH-NUMBER-OF-MUDSPLASHES condition, NOT-HIGHLIGHTED condition, HIGHLIGHTED condition). Similarly, undetected and no changes should not differ from each other.

We analyzed the association between attentional processes (as reflected by the N2pc amplitude), post-perceptual processes of successful change detection (as reflected by the P3 component for detected changes) and the sensitivity *d'* (measured with *d'*) with Pearson correlations. To test whether the N2pc and the P3 could predict the sensitivity for changes, additional stepwise multiple regression analyses were performed with the manifest sensitivity *d'* serving as dependent variable and the manifest N2pc amplitude and the manifest P3 amplitude serving as independent variables. For these regression analyses each variable was averaged across conditions (LOW-NUMBER-OF-MUDSPLASHES condition, HIGH-NUMBER-OF-MUDSPLASHES condition, NOT-HIGHLIGHTED condition, HIGHLIGHTED condition).

In case of multiple comparisons, *p* was adjusted according to Bonferroni. Effect sizes were calculated by means of Hay's ω or Cohen's *d*.

Latent state-trait model of the N2pc and the P3. Subsequently, we applied an LST model for the N2pc amplitude for detected changes in order to test to what extent individual differences in the allocation of attention in change blindness are due to the person, to the situation, to the method, or to measurement errors (cf. Steyer et al., 1999). To assess influences on individual differences in successful and aware post-perceptual change processing, we applied another LST model for the P3 amplitude for detected changes. Similarly to the LST model of *d'*, in both models, three measurement occasions were included and three method factors, for the LOW-NUMBER-OF-MUDSPLASHES condition, the HIGH-NUMBER-OF-MUDSPLASHES condition and the HIGHLIGHTED condition, were set up.

The LST model for the N2pc and the P3 were by using the maximum likelihood algorithm (ML), because some values were missing (N2pc: elven values at measurement occasion one, ten values at measurement occasion two, and thirteen values at measurement occasion three thirteen; P3: two values at measurement occasion one, one value at measurement occasion two, and one value at measurement occasion three). This happened because in some conditions no changes were detected and thus no N2pc or no P3 for detected changes could be analyzed. Again, the general model fits were evaluated by indices of the χ^2 statistics, the CFI and the RMSEA. The critical ratio and its standard error were used to assess the significance ($\alpha \leq .05$) of the single model parameters. Next, coefficients of trait specifity, coefficients of occasion and method specifity and the reliabilities of the measurements were assessed for the N2pc amplitude and the P3 amplitude.

Latent correlations. Finally, we analyzed the latent trait correlation between the sensitivity *d'*, the N2pc, and the P3 to assess the true relation of participants' sensitivity for changes and attentional and post-perceptual change processing. The LST models were fitted to their covariance matrices by using the maximum likelihood algorithm (ML), because some values for the N2pc amplitude and the P3 amplitude were missing (see above).

Further measures

To assess the discriminative validity of the sensitivity for changes, its relation to further constructs was tested: general intelligence, assessed with the APM (Advanced

Progressive Matrices; Raven, Court, & Raven, 1994), mental speed, assessed with the Hick Paradigm (Neubauer, Bauer, & Höller, 1992) and the ZVT (Zahlenverbindungstest; Oswald & Roth, 1987), and the Big Five personality traits, assessed with the NEO-FFI (Costa & McCrae, 1992b). We analyzed correlations of the manifest measure of sensitivity *d'* and the respective manifest further measures. Then correlations of latent sensitivity *d'* and the respective manifest further measures were computed.

Advance Progressive Matrices (APM). A computer adapted version of the APM was applied to assess participants' general intelligence. We followed the recommendation of the test manual and used the number of correct items of the second set (36 items) as indicator of participants' performance. Internal consistency was high in the current study (Cronbach's alpha = .88).

Hick Paradigm. The Hick paradigm is a simple choice and reaction time task, which measures the speed of information processing (e.g., A. R. Jensen, 1987). Reaction time is linearly related to the amount of information in a reaction time task (Hick, 1952). No choice is necessary when no information is presented in the simple reaction condition (0-bits of information), when observers have to choose between two or four alternatives, a binary decision decision (1-bit) or two binary decisions (2-bit) are necessary, respectively (e.g., Neubauer, 1991, 1997). Reaction time should be negatively related to psychometric intelligence. A modified version of the paradigm by Neubauer et al. (1992) was applied, adapted for use on the computer without a home button. We implemented a 1-bit condition and a 2-bit condition. In the 1-bit condition, two squares appeared on the screen at fixed position, whereas in the 2-bit condition these two squares varied pseudo-randomly in two of four locations. Participants were asked to indicate the appearance of the squares as fast as possible. In each condition, participants passed a short exercise. Spearman-Brown corrected reliabilities, measured with odd-even split, ranged from .98 in the 1-bit condition to .99 in the 2-bit condition.

Zahlenverbindungstest (ZVT). The ZVT, a paper and pencil test, was used as a second marker of the mental speed component of general intelligence. This measure includes four number matrices (A to D); each consists of numbers 1 to 90 in random order. Participants are asked to connect the numbers in sequence as fast as possible. Mean execution time serves as dependent measure. In the present study, the ZVT yielded a high internal consistency (Cronbach's alpha = .96).

NEO Five Factor Inventory (NEO-FFI). Finally, a 60-item version of the NEO-FFI was used to assess participants' Big Five personality with the indices Openness to Experience, Conscientiousness, Extraversion, Agreeableness, and Neuroticism. In line with former research, these scales yielded good internal consistencies, with Cronbachs' alphas ranging from .73 for Agreeableness to .86 for Neuroticism.

Results

Behavioral data

Participants responded correctly to 43.11% of the luminance changes (standard error of mean =2.38%) and to 95.23 % (standard error of mean = .59%) of the no changes, averaged across measurement occasions and conditions. Table 2 displays the mean accuracy rates for no changes and or luminance changes and values of sensitivity *d'* and response bias *c* as a function of condition and of the single three measurement occasions.

First, we investigated whether the sensitivity for changes *d'* and or the response bias *c* differed between conditions. Data were analyzed separately for number of mudsplashes (LOW- vs. HIGH-NUMBER-OF-MUDSPLASHES) and highlighted change positions (NOT-HIGHLIGHTED condition vs. HIGHLIGHTED condition). Participants were more sensitive to changes with increasing number of mudsplashes, $F(1,59) = 112.4$, $p < .001$, $\omega^2 = .65$, and when change positions were highlighted in red color compared to not-highlighted change positions, $F(1,59) = 408.3$, $p < .001$, $\omega^2 = .87$. Moreover, participants answered more conservatively with increasing number of mudsplashes, $F(1,59) = 38.4$, $p < .001$, $\omega^2 = .39$, and when change positions were not-highlighted compared to highlighted change positions, $F(1,59) = 112.2$, $p < .001$, $\omega^2 = .65$.

Electrophysiological data

Electrophysiological correlate of selective attention (N2pc). The N2pc was analyzed as an electrophysiological correlate of selective attention (e.g., Eimer, 1996; Luck & Hillyard, 1994a), averaged across all three measurement occasions. Figure 2 displays difference waveforms of the N2pc component in the ERP elicited by the onset of a change at posterior electrodes (PO7/PO8), contralateral and ipsilateral to the change location for detected and undetected changes.

We tested if the N2pc amplitude was elicited by detected changes and by undetected changes. T-tests showed that the N2pc was only elicited for detected changes in all four conditions, i.e. low-number-of-mudsplashes, *t*(59) = 4.6, *p* < .001, *d* = .59, NOT-HIGHLIGHTED, *t*(59) = 6., *p* < .001, *d* = .47, HIGH-NUMBER-OF-MUDSPLASHES, *t*(59) = 3.6, *p* = .003, *d* = .84, and HIGHLIGHTED, *t*(59) = 10.2, *p* < .001, *d* = 1.03. It was absent, however, for undetected changes in all conditions, all *t*s ≤ 1.2, all *p*s ≥ 233.

Electrophysiological correlate of post-perceptual processes (P3). The P3 was analyzed as an electrophysiological correlate of post-perceptual change processing (e.g., Koivisto & Revonsuo, 2003). Figure 3 shows grand-averaged ERP waveforms elicited by the onset of a change at posterior central electrode Pz, for detected changes, undetected changes, and no changes.

We tested if the P3 amplitude was increased for detected changes in comparison to undetected changes (cf. Koivisto & Revonsuo, 2003). T-tests showed that the P3 was increased for detected changes in all four conditions, i.e. LOW-NUMBER-OF-MUDSPLASHES, *t*(59) = 5.8, *p* < .001, *d* =.55, NOT-HIGHLIGHTED, *t*(59) = 5.6, *p* < .001, *d* =.46, HIGH-NUMBER-OF-MUDSPLASHES, *t*(59) = 4.7, *p* < .001, *d* = .45, and HIGHLIGHTED, *t*(59) = 8.1, *p* < .001, *d* = .77. Undetected changes and no changes, however, did not differ from each other in all conditions, all *t*s ≤ 1.0.

Manifest correlations. The relationship of sensitivity *d'*, the N2pc for detected changes, and the P3 for detected changes was analyzed with correlational analyses (cf. Table 3). The N2pc amplitude and the sensitivity for changes were related to each other in all conditions with the lowest correlation in the HIGH-NUMBER-OF-MUDSPLASHES, *r* = -.26, *p* = .041, and the highest correlation in the HIGHLIGHTED condition, *r* = -.44, *p* < .001. Also the P3 amplitude and the sensitivity for changes were related to each other in the condition with a low number of mudsplashes, *r* = .49, *p* < .001, with a high number of mudsplashes, *r* = .47, *p* < .001, and when change positions were not highlighted, *r* = .40, *p* = .003. When change positions were highlighted the correlation reached marginal significance, *r* = .30, *p* = .076. Moreover, the N2pc was moderately related to the P3 in the condition with high number of mudsplashes, *r* = -.31, *p* = .016**,** whereas the correlation did not reach significance in the remaining three conditions. These correlations might serve as a first empirical evidence of the relation of the sensitivity for changes and attentional selection and post-perceptual processing as its underlying processes. Attentional selection and post-perceptual processing may be seen as rather distinct processes.

Manifest regression analyses. Regression analyses showed that the N2pc amplitude for detected changes predicted sensitivity *d'*, $F(1,58) = 14.5$, $\beta = -.45$, $\beta = -.45$, $p < .001$, $R^2 = .19$. Similarly, also the P3 amplitude predicted sensitivity *d'*, $F(1,58) = 14.7$, $\beta = .45$, $p < .001$, $R^2 = .19$ with $\beta = .45$, $p < .001$. When both predictors were included into the regression analysis, the N2pc, $\beta = -.23$, $p = .004$, and the P3, $\beta = .05$, $p = .004$, predicted sensitivity *d'*, $F(2,57) = 12.8$, $p < .001$, $R^2 = .29$. Thus, both attentional selection and post-perceptual processing independently contribute to the sensitivity for changes.

Manifest correlations of further measures. Table 4 shows the manifest correlations of sensitivity *d'* with further performance measures. Sensitivity for changes was related with general intelligence, mental speed, neuroticism, and extraversion, but with the latter only in the HIGHLIGHTED condition.

Latent state-trait models

To assess the latent influence of the person, the situation, the method and of measurement error, LST models were set up, separately for the three variables the *sensitivity for changes d'*, the *N2pc amplitude* (detected changes only), and the *P3 amplitude*. Stable inter-individual differences are reflected by a high proportion of variance in a latent trait variable, whereas the influence of methods and situations should be low. If selective attention and/or post-perceptual change processing are underlying mechanisms of the ability to detect changes, this should be reflected by the N2pc and the P3 in the ERP. Figure 4, Figure 5, and Figure 6 show the final versions of the LST models for sensitivity *d'*, the N2pc, and the P3, respectively. Table 5 presents the estimated variances with their standard errors and the critical ratios of the model parameters of sensitivity *d'*, the N2pc amplitude, or the P3 amplitude in the LST models.

Latent state-trait model of sensitivity *d'*. We began with setting up a maximally restricted model by setting all path coefficients to one and by equalizing the variances of the measurement errors (e_i) and of the state residuals (SR_k). Afterwards, the number of free parameters was gradually increased to improve acceptance of the model fit. All variances of the measurement errors (e_i) and the path coefficients between the single measurement occasions (S_i) and the observed variables of the HIGHLIGHTED condition were relaxed. The variances of the state residuals SR_1 and SR_2, were equalized, because differences between these state residuals were minimal. As a consequence of insignificance, the variance of the state residual at measurement occasion two (SR_2), the method factor of the HIGH-NUMBER-OF-MUDSPLASHES condition (M_1) and the measurement error of the LOW-NUMBER-OF-MUDSPLASHES condition (e_9) at measurement occasion three were set to zero (cf. Figure 4). This model could be accepted, $\chi2(60) = 72.6$, $p = .128$, CFI = .74, RMSEA = .06. Based on the observed variables in the accepted model, standard LST parameters were computed. Table 6 shows the LST model parameters for the observed variables, separately for *sensitivity d'*, the *N2pc amplitude*, and the *P3 amplitude*. All measurements of the sensitivity for changes were highly reliable, ranging between .80 and .98, and all occasion specifities were low, ranging between .00 and .14. In the LOW-NUMBER-OF-MUDSPLASHES condition, the NOT-HIGHLIGHTED condition, and the HIGH-NUMBER-OF-MUDSPLASHES condition trait specifities were great, ranging between .63 and .86, whereas method specificities were low, ranging between .00 and .10. In the HIGHLIGHTED condition, however, trait specifities were smaller, ranging between .43 and .52, and method specifities increased, ranging between .28 and .37.

Latent state-trait model of the N2pc. We used the same procedure to model the N2pc. As a consequence of insignificance, the variance of the state residuals at measurement occasion one (SR_1), two (SR_2), and three (SR_3), and the variance of the method factors of THE LOW-NUMBER-OF-MUDSPLASHES condition (M_1) and the HIGH-NUMBER-OF-MUDSPLASHES condition (M_2) were set to zero. This model could be accepted, $\chi2(61) = 65.9$, $p = .311$, CFI = .95, RMSEA= .04 (cf. Figure 5). Based on the observed variables in the accepted model, standard LST parameters were computed. As indicated in Table 6, occasion specifities of the N2pc were low in all conditions, i.e. all occasion specifities were .00. All reliabilities ranged between .11 and .46, the trait specifities ranged between .11 and .27, and all method specifities were .00 in the LOW-NUMBER-OF-MUDSPLASHES condition, the NOT-HIGHLIGHTED condition and the HIGH-NUMBER-OF-MUDSPLASHES condition. In the HIGHLIGHTED condition, however, reliabilities, ranged between .50 and .59, trait specifities ranged between .28 and .32, and method specifities ranged between .22 and .29.

Latent state-trait model of the P3. We used the same procedure to model the P3. As a consequence of insignificance, the variance of the state residual at measurement occasion two (SR_2), the variance of the method factors of the LOW-NUMBER-OF-MUDSPLASHES condition (M_1) and the HIGH-NUMBER-OF-MUDSPLASHES condition (M_2) were set to zero. To improve the model fit, correlations between measurement error one with two, *r* = .564, *p* = .004, and between measurement error nine with ten, *r* = .455, *p* = .007, had to be relaxed. The model showed a marginally acceptable fit, $\chi 2(57) = 94.4$, *p* = .001, CFI = .95, RMSEA = .11, (cf. Figure 6). As the RMSEA may underestimates the model fit for small sample sizes (Kenny, Kaniskan, & McCoach, 2014), we accepted the model. Based on the observed variables in the accepted model, standard LST parameters were computed (cf. Table 6). Trait specifities ranged between .46 and .83. All occasion specifities ranged between .00 and .16, and all method specifities ranged between .00 and .09, whereas reliabilities ranged between .55 and .99.

Latent correlations. The relationship of the latent trait variables sensitivity for changes, selective attention (N2pc amplitude), and post-perceptual processes (P3 amplitude) were investigated. Latent sensitivity *d'* and the amplitude of the latent N2pc component were moderately correlated, *r* = -.49, *p* = .004 (model fit was acceptable, $\chi 2(264) = 386.3$, *p* < .001, CFI = .89, RMSEA = .09), as well as latent sensitivity *d'* and the amplitude of the latent P3 component, *r* = .41, *p* = .005 (model fit was marginally acceptable, $\chi 2(261) = 476.2$, *p* < .001, CFI = .88, RMSEA = .12). That is, selective attention and post-perceptual processes are related to individual differences in change detection performance. Moreover, latent N2pc and latent P3 were also correlated, *r* = -.41, *p* = .014 (model fit was acceptable, $\chi 2(261) = 361.1$, *p* < .001, CFI = .90, RMSEA = .08).

Latent correlations of further measures. Finally, correlations of latent sensitivity *d'* and the manifest variables general intelligence, mental speed and the Big Five were computed to assess the validity of the sensitivity for changes. Table 7 displays the underlying model fits. The relation of latent sensitivity *d'* and mainfest general intelligence, as measured with the APM, was significant, *r* = .43, *p* = .020. Latent sensitivity *d'* was not related to the manifest variable mental speed, as assessed with the ZVT, *r* = -.18, *p* = .388, and it was only marginally related to the manifest variable mental speed, as assessed with the Hick Paradigm, *r* = -.33, *p* = .071. Latent *d'* was not related to the manifest Big Five personality traits (openness, *r* = .12, *p* = .446; conscientiousness, *r* = .23, *p* = .196; extraversion, *r* = -.15, *p* = .429; agreeableness, *r* = -.07, *p* = .704; neuroticism, *r* = -.13, *p* = .465).

Discussion

The first aim of the present study was to assess whether individual differences in change blindness are a trait-like characteristic of the person. A longitudinal design allowed investigating the consistency of individual differences in change blindness across several measurement occasions. The results show that the sensitivity for changes is a stable trait, i.e. a person is consistently able to detect changes better than others, across different situation and measurement methods.

First, the portion of the trait specific variance of the sensitivity for changes is high, ranging from .63 to .86. Thus, 63% to 86% of the variance in the manifest measure of the sensitivity for changes is due to consistent individual differences in a latent trait. This trait specifity corresponds to a trait specifity that is seen in standard personality variables, i.e. the Big Five personality traits (Deinzer et al., 1995), which are characterized by a high validity and stability (e.g., Costa & McCrae, 1992a). It is somewhat lower than the trait specifity of a standard general intelligence measure (Danner, Hagemann, Schankin, Hager, & Funke, 2011).

Second, the portion of the occasion specific variance ranged between .00 and .14. Thus, 0% to 14% of the variance of the manifest variables are due to effects of the situation or the interaction between person and situation. This occasion specifity corresponds to an occasion specifity that is seen in a standard personality variables (Deinzer et al., 1995). However, this latent source of variance was zero for a standard intelligence measure (Danner et al., 2011). The small effect might be due to fatigue or participants' motivation to perform adequately in the task. Only few studies addressed the effects of situational variables on change blindness. For example, Sänger and Wascher (2011) investigated the effects of extrinsic motivation, in the form of a monetary reward, on change detection. In a competitive task, participants were instructed to detect either a location change or an orientation change and to ignore irrelevant stimuli in a competitive task. The researchers reported an influence of motivation on change detection performance. Therefore, we recommend systematically assessing motivation or fatigue or other possible situational factors on individual differences in change blindness in future studies.

Third, the portion of the method specific variance, which ranged between .00 and .10, was rather low and reliability, which was between .77 and .98, was rather high. Both psychometric parameters suggest that technical measurement problems played a subordinate role for the assessment of individual differences in change blindness. However, the effect of the experimental method increased and the trait specific effect on change blindness decreased when change positions were permanently highlighted. This finding can be explained by a decreased task difficulty. Task demands can be manipulated by the characteristics of the stimuli (Pringle et al., 2001). We suggest that tasks that are too easy do not differentiate sufficiently between persons that are high or low change blind because of a ceiling effect due to a restriction of variances.

Complementing these psychometric analyses, we also investigated the convergent and discriminant validity of change blindness measures with respect to standard measures of personality and intelligence. We found a negative manifest relation between the sensitivity for changes and neuroticism, extraversion, and mental speed. These correlations were not explained by individual differences in the sensitivity for changes suggesting that they might be due to variations in the measurement errors, in the measurement occasions, or in the experimental methods. Thus, there were essentially null relations of the trait sensitivity for changes with all personality traits, which suggest discriminant validity of change blindness measures. Furthermore, there was a positive association between individual differences in the sensitivity for changes and general intelligence with a size of .42. This finding may tentatively suggest that measures of individual differences in change blindness and intelligence may tap at least in part the very same cognitive process, although the magnitude of this overlap is rather small. Below we will discuss some preliminary evidence that may help to shed some light on the nature of this overlapping process.

To conclude, this is the first paper which showed that individual differences in change blindness are a trait-like characteristic of the person. Practical consequences are obvious. Individual differences in change blindness may be related to performance in real life task that make a demand on the detection of changes in a multitude of circumstances, e.g. in navigation, surveillance, or driving (cf. O'Regan et al., 1999; Simons & Levin, 1998). In particular, future change blindness tasks may, e.g. help to ensure that changed rules of the road or modified traffic signs are so salient that they can be detected by every car driver, also by those with low change detection abilities. Furthermore, e.g. the detection of newly developed lung cancer is an important task for a pulmonologist. As the doctor has to scan several X-ray images a day, he or she has to possess a high ability in the detection of even small changes in the pictures. The application of further developed change detection tasks might also be useful in addition to standard measures, such as general intelligence tests, for the diagnosis of (professional) aptitude, e.g., of car drivers, airplane pilots, or surgeons. Future research may investigate to which extent individual differences in change blindness can predict the performance in these tasks.

The second aim of the current study was to assess which neurocognitive processes contribute to individual differences in change blindness. We can say that there are individual differences in distinct neurocognitive processes that are associated with the sensitivity for changes. One of these processes is related to the N2pc component in the ERP and the other is related to the P3 component.

First, there was a negative relationship between the magnitude of the N2pc and the sensitivity for changes. Individuals who showed a rather large N2pc amplitude at about 330 ms afters stimulus onset also showed a better change detection with mean reaction times of about 1190.5 ms after stimulus onset (SD = 255.4). This finding suggests that individual differences exist in the allocation of selective attention in change detection (cf. Eimer, 1996). This conclusion is in accordance with former research, which showed that individual differences in attentional stimulus processing facilitate or complicate the detection of changes (e.g., Byrne & Eysenck, 1995; McGlynn et al., 2008). Furthermore, it has been suggested that the N2pc amplitude is greater in more difficult tasks when more attention has to be allocated onto the change (e.g., Luck & Hillyard, 1994b). Thus, we suggest that individual differences in change blindness are associated with observers' individual limitation of attentional resources (cf. Masuda & Nisbett, 2006; Simons & Ambinder, 2005), which vary systematically between persons (e.g., Cowan, 2000; Rensink, 2000b). Moreover, there was a small situational effect on the N2pc amplitude, again explainable, e.g. by motivation (Sänger & Wascher, 2011). When change positions were highlighted, however, the effect of the method increased, i.e., the task became too easy to differentiate sufficiently between persons. It should be noted that a great measurement error variance was observed, possibly due to the fact that the N2pc component is computed from the difference from ipsilateral and contralateral activity, subtracting the true scores from each other (for a review on difference scores see Zumbo, 1999).

Second, there was a positive relationship between the magnitude of the P3 and the sensitivity for changes. Individuals who showed an increased P3 amplitude at about 500 ms afters stimulus onset also showed a better sensitivity for changes after stimulus onset. This finding suggests that post-perceptual cognitive processes are also related to the ability to detect changes. Thus, later phases, e.g. the aware processing and evaluation of the change for ongoing decision making (cf. Koivisto & Revonsuo, 2003; O'Connell et al., 2012), can explain some part of individual differences in change detection. This finding extends former research, which indicated that the P3 component is influenced by individual differences, e.g. in extraversion or in age (e.g., D. Friedman, 2008). Moreover, we found a small influence of the situation. It is well known that situational determinants, e.g., fatigue, exercise or menstrual cycle, affect the P3 component (Polich & Kok, 1995).

Furthermore, attentional change processing and post-perceptual change processing can be regarded as related, but distinct processes. This is in line with the finding that only attended changes can be reported consciously (e.g., O'Regan et al., 2000). Moreover, a stepwise regression indicated that the inclusion of the N2pc amplitude as a first predictor allowed explaining 19 % of the variance in the sensitivity for changes, whereas the amount of explained variance increased significantly to 29% after inclusion of the P3 amplitude as a second predictor. This finding suggests that the N2pc and the P3 essentially tap distinct neurocognitive processes which both contribute to and amplify the individual sensitivity for changes.

Supplementing these findings, there was a small overlap of measures of individual differences in change blindness and intelligence, which may tap at least in part the very same cognitive process. To shed some light on the nature of this overlapping process, the N2pc and the P3 component were correlated with general intelligence, as measured with the APM. We found a significant relation of individual differences in the N2pc amplitude and general intelligence, $r = -.44$, $p = .008$ (acceptable model fit, $\chi2(72) = 80.0$, $p < .242$, CFI = .92, RMSEA = .04). Also the relation of the P3 amplitude with general intelligence reached significance, $r = .40$, $p = .005$ (marginally acceptable model fit, $\chi2(68) = 106.7$, $p = .002$, CFI = .95, RMSEA = .10). Moreover, a stepwise regression indicated that the inclusion of the N2pc amplitude as a first predictor allowed explaining 19 % of the variance in the sensitivity for changes, whereas the amount of explained variance increased significantly to 29% after inclusion of the P3 amplitude as a second predictor. Together, these results show a relation of both attentional and post-perceptual change processing with intelligence. Former research offers possible explanations for this observation. For example, individual differences in working memory capacity, which are strongly related to intelligence (Engle, Tuholski, Laughlin, & Conway, 1999) and become apparent in the size of the P3 amplitude (Nittono et al., 1999), might explain this relationship. Moreover, increased working memory load might also increase the inference of distractors (Lavie, Hirst, de Fockert, & Viding, 2004) and thus complicate the allocation of attention onto the change. Thus, our findings suggest mainly one common neurocognitive factor in individual differences in change blindness and general intelligence.

Conclusion

The present study showed that individual differences in change blindness are due to a trait. That is, persons differ systematically in their sensitivity for changes. A talented pilot, race driver, surgeon, or soccer goal keeper – they all have one thing in common: the ability to detect changes in the environment better than the average. Future studies should clarify predictive validity and applicability of change blindness tasks for real-life and the diagnosis of (professional) aptitude which make a demand on the ability to detect changes in the environment. Moreover, change blindness is a multiple-cause phenomenon. There are least two distinct mechanisms which contribute to individual difference in the sensitivity for changes: An earlier attentional phase and a later post-perceptual phase of change processing, necessary for ongoing change evaluation and decision making.

Footnotes

[1] In this analysis we only compare the LOW-NUMBER-OF-MUDSPLASHES condition with the HIGH-NUMBER-OF-MUDSPLASHES condition (both presented in one block), but we did not include the not-highlighted condition, to avoid a confound between the number of mudsplashes with the way of presentation. Because the LOW-NUMBER-OF-MUDSPLASHES condition and THE HIGH-NUMBER-OF-MUDSPLASHES condition were presented mixed together, i.e., the number of mudsplashes was not predictable from trial to trial, task demands increased in general and participants' uncertainty might be higher than in the NOT-HIGHLIGHTED condition.

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Ethical Standards

All human studies have been approved by the appropriate ethics committee and have therefore been performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and its later amendments. All persons gave their informed consent prior to their inclusion in the study. Details that might disclose the identity of the subjects under study were omitted. The manuscript does not contain clinical studies or patient data.

Tables

Table 1. Overview of the different experimental conditions.

Condition	**Number of Mudsplashes**	**Highlighted**	**Trials per measurement occasion**	**Trials overall**
LOW-NUMBER-OF-MUDSPLASHES	4	No	252	756
HIGH-NUMBER-OF-MUDSPLASHES	8	No	252	756
NOT-HIGHLIGHTED change positions	6	No	252	756
HIGHLIGHTED change positions	6	Yes	252	756

Table 2. Mean accuracy rate in percentage for no changes and luminance changes and values of sensitivity *d'* and response bias *c* as a function of condition (LOW-NUMBER-OF-MUDSPLASHES, HIGH-NUMBER OF MUDSPLASHES, NOT-HIGHLIGHTED, and HIGHLIGHTED) and of the single three measurement occasions (*SE* = standard error of mean).

Measurement occasion	**Condition**	**No Change *(SE)***	**Luminance Change (*SE)***	**Sensitivity *d' (SE)***	**Response bias *c (SE)***
S_1	Low Muds	95.10(.74)	31.65(2.61)	1.26(.11)	1.21(.06)
	High Muds	94.30(.80)	22.57(2.03)	.89(.08)	1.30(.06)
	Not High	89.83(.13)	26.70(2.08)	.77(.09)	1.10(.06)
	High	96.13(.54)	75.37(2.90)	2.78(.12)	.55(.06)
S_2	Low Muds	95.95(.57)	41.90(2.95)	1.65(.11)	1.08(.05)
	High Muds	95.30(.65)	31.50(2.59)	1.23(.10)	1.25(.05)
	Not High	94.08(.94)	35.25(2.47)	1.35(.10)	1.10(.05)
	High	96.48(.78)	70.62(3.08)	2.70(.12)	.66(.06)
S_3	Low Muds	96.40(.57)	38.95(2.76)	1.65(.11)	1.15(.05)
	High Muds	95.70(.70)	25.72(2.62)	1.15(.10)	1.34(.05)
	Not High	96.98(.49)	39.73(2.77)	1.72(.11)	1.17(.05)
	High	96.48(.65)	77.35(2.88)	2.95(.12)	.54(.06)
Overall	Low Muds	95.82(.49)	37.50(2.53)	1.54(.10)	1.13(.04)
	High Muds	95.10(.56)	26.59(1.99)	1.10(.09)	1.27(.04)
	Not High	93.63(.75)	33.89(2.17)	1.24(.09)	1.08(.04)
	High	96.37(.56)	74.44(2.84)	2.78(.12)	.58(.05)

Note. LOW-NUMBER-OF-MUDSPLASHES condition (Low Muds); HIGH-NUMBER-OF-MUDSPLASHES condition (High Muds).

Table 3. Manifest correlations of sensitivity *d'*, the N2pc amplitude for detected changes, and the P3 amplitude for detected changes.

		Sensitivity *d'*				**N2pc**				**P3**			
	Stimulation	Low Muds	High Muds	Not High	High	Low Muds	High Muds	Not High	High	Low Muds	High Muds	Not High	High
Sensitivity *d'*	Low Muds	1											
	High Muds	.93**	1										
	Not High	.92**	.93**	1									
	High	.75**	.71**	.76*	1								
N2pc	Low Muds	-.30*	-.18	-.28*	-.26*	1							
	High Muds	-.28*	-.26*	-.28*	-.26*	.20	1						
	Not High	-.38*	-.30*	-.36*	-.35*	.48**	.29*	1					
	High	-.32*	-.23^{+}	-.33*	-.44**	.43*	.28*	.53**	1				
P3	Low Muds	.49**	.48**	.43*	.41*	.06	-.36**	-.25^{+}	-.31	1			
	High Muds	.46**	.47**	.42*	.42*	.14	-.31*	-.16	-.27*	.94**	1		
	Not High	.44**	.42*	.40*	.44**	-.00	-.34*	-.20	-.32*	.32**	.88**	1	
	High	.29*	.27*	.22^{+}	.30*	.05	-.36*	-.15	-.20	.86**	.83**	.88**	1

Note. LOW-NUMBER-OF-MUDSPLASHES condition (Low Muds), HIGH-NUMBER-OF-MUDSPLASHES condition (High Muds), NOT-HIGHLIGHTED condition (Not High), HIGHLIGHTED condition (High); **$p < .001$; *$p < .005$; $^{+}p < .010$.

Table 4. Manifest correlations of sensitivity *d'* and further performance measures (general intelligence, mental speed, Big Five).

		Sensitivity *d'*				**Intelligence**	**Mental speed**		**Big Five**				
	Stimulation	Low Muds	High Muds	Not High	High	APM	ZVT	Hick	Open	Consc	Extra	Agree	Neuro
Sensitivity *d'*	Low Muds	1											
	High Muds	.93**	1										
	Not High	.92**	.93**	1									
	High	.75**	.71**	.76*	1								
Intelligence	APM	.45**	45**	. 46**	.33*	1							
Mental speed	ZVT	-.46**	-.38*	-.38*	-.58**	-.19	1						
	Hick	-.47**	-.46**	-.45**	-.51**	-.22^{+}	.43*	1					
Big Five	Open	.15	.09	.05	.02	.08	-.01	.18	1				
	Consc	.12	.21	.21	.24^{+}	.06	-.10	-.01	-.13	1			
	Extra	.18	.15	.15	.34*	.07	-.48**	-.17	-.04	.27*	1		
	Agree	.08	-.04	.11	.23^{+}	-.03	-.26*	.08	.15	.24^{+}	.46**	1	
	Neuro	-.39*	-.37*	-.36*	-.36*	-.28*	.42*	.28*	.15	-.25^{+}	-.40*	-.13	1

Note. LOW-NUMBER-OF-MUDSPLASHES condition (Low Muds), HIGH-NUMBER-OF-MUDSPLASHES condition (High Muds), NOT-HIGHLIGHTED condition (Not High), HIGHLIGHTED condition (High); APM (Advanced Progressive Matrices; Raven et al., 1994); Hick (Hick paradigm; Neubauer et al., 1992); ZVT (Zahlenverbindungstest; Oswald & Roth, 1987) Open (openness); Consc (conscientiousness); Extra (extraversion); Agree (agreeableness); Neuro (neuroticism); **$p < .001$; *$p < .005$; $^{+}p < .010$.

Table 5. Estimated variances (SE = standard error of mean) and critical ratios (CR) of sensitivity *d'*, the N2pc amplitude for detected changes, and the P3 amplitude for detected changes.

Model parameter	**Sensitivity *d'***		**N2pc**		**P3**	
	Var (*SE*)	**CR**	**Var (*SE*)**	**C.R.**	**Var (*SE*)**	**CR**
Trait	.24(.06)	3.88**	.83(.23)	3.56**	24.93(4.89)	5.10**
M_1 (Low Muds)	.03(.01)	2.50*	.00(.00)		.00(.00)	
M_2 (High Muds)	.00(.00)		.00(.00)		.00(.00)	
M_3 (Highlighted)	.14(.04)	3.21*	.68(.28)	2.43*	2.76(.88)	3.14*
SR_1	.04 (.01)	3.48**	.00(.00)		6.73(1.94)	3.47**
SR_2	.00(.00)		.00(.00)		.00(.00)	
SR_3	.04(.01)	3.48**	.00(.00)		4.76(1.49)	3.19*
e_1	.07(.02)	3.23*	2.30(.49)	4.73**	13.09(2.94)	4.46**
e_2	.03(.01)	2.36*	4.67(.94)	4.95**	10.48(2.46)	4.26**
e_3	.08(.02)	4.17**	3.42(.68)	5.02**	10.65(2.45)	4.35**
e_4	.07(.03)	2.63*	1.14(.29)	3.92**	2.19(1.10)	2.00*
e_5	.08(.02)	3.59**	6.63(1.30)	5.11**	6.12(1.41)	4.36**
e_6	.04(.01)	3.08*	6.77(1.34)	5.07**	9.04(1.94)	4.67**
e_7	.06(.02)	3.70**	1.80(.39)	4.64**	8.02(1.74)	4.62**
e_8	.08(.03)	2.90**	.96(.25)	3.76**	2.52(.92)	2.74*
e_9	.00(.00)		4.26(.85)	5.01**	.96(2.02)	4.44**
e_{10}	.05(.02)	3.25*	5.37(1.01)	4.89**	24.10(4.79)	5.03**
e_{11}	.08(.02)	4.06**	3.40(.69)	4.94**	3.60(1.22)	2.95*
e_{12}	.05(.02)	2.00*	1.59(.37)	4.37**	4.88(1.38)	3.53**

Note: ** $p < .001$, *$p < .050$: $^{+}p < .10$; *d'* = sensitivity *d'*; variances (Var); method factors (M_1 – M_3); state residuals (SR_1 – SR_3); LOW-NUMBER-OF-MUDSPLASHES condition (Low Muds.); HIGH-NUMBER-OF-MUDSPLASHES condition (High Muds).

Table 6. Reliabilities, trait specifities, measurement specifities, and occasion specifities for the observed variables of sensitivity *d'*, the N2pc amplitude for detected changes, and the P3 amplitude for detected changes.

		Sensitivity *d'*				**N2pc**				**P3**			
	Stimulation	**Trait Spe(Y)**	**Occ Spec(Y)**	**Meth Spe(Y)**	**Rel(Y)**	**Trait Spe(Y)**	**Occ Spec(Y)**	**Meth Spe(Y)**	**Rel(Y)**	**Trait Spe(Y)**	**Occ Spec(Y)**	**Meth Spe(Y)**	**Rel(Y)**
S_1	Low Muds	.63	.11	.08	.82	.27	.00	.00	.27	.56	.15	.00	.71
	High Muds	.77	.13	.00	.90	.15	.00	.00	.15	.59	.16	.00	.75
	Not High	.67	.11	.00	.77	.20	.00	.00	.20	.59	.16	.00	.75
	High	.50	.08	.28	.86	.32	.00	.25	.57	.72	.19	.08	.99
S_2	Low Muds	.69	.00	.09	.78	.11	.00	.00	.11	.80	.00	.00	.80
	High Muds	.86	.00	.00	.86	.11	.00	.00	.11	.73	.00	.00	.73
	Not High	.80	.00	.00	.80	.46	.00	.00	.46	.76	.00	.00	.76
	High	.52	.00	.30	.82	.30	.00	.29	.59	.83	.00	.09	.92
S_3	Low Muds	.77	.11	.10	.98	.16	.00	.00	.16	.81	.12	.00	.93
	High Muds	.73	.14	.00	.94	.13	.00	.00	.13	.46	.09	.00	.55
	Not High.	.67	.13	.00	.80	.20	.00	.00	.20	.75	.14	.00	.89
	High	.43	.07	.37	.87	.28	.00	.22	.50	.67	.13	.08	.88

Note. *d'* = sensitivity *d'*; N2pc = amplitude of the N2pc for detected changes; P3 = amplitude of the P3 for detected changes; measurement occasion or situation (S_1–S_3); LOW-NUMBER-OF-MUDSPLASHES condition (Low Muds), HIGH-NUMBER-OF-MUDSPLASHES condition (High Muds), NOT-HIGHLIGHTED condition (Not High), HIGHLIGHTED condition (High), observed variable (Y); trait specifity (Trait Spe); occasion specifity (Occ Spe); method specifity (Meth Spe); reliability (Rel).

Table 7. Model fits of the single LST-models including correlations of sensitivity *d'* with the respective manifest variables for general intelligence, mental speed, and the Big Five personality traits.

		Model fit			
Manifest variable		χ2(df)	*p*	CFI	RMSEA
Intelligence	APM	83.2(71)	.153	.75	.05
Mental speed	ZVT	82.3(71)	.169	.74	.05
	Hick	77.4(71)	.282	.84	.04
Big Five	Openness	80.0(71)	.217	.79	.05
	Extraversion	86.5(71)	.102	.67	.06
	Agreeableness	83.7(71)	.144	.74	.06
	Conscientiousness	83.1(71)	.155	.71	.05
	Neuroticism	81.4(71)	.187	.78	.05

Note: PM (Advanced Progressive Matrices; Raven et al., 1994); Hick (Hick paradigm; Neubauer et al., 1992); ZVT (Zahlenverbindungstest; Oswald & Roth, 1987).

Figures

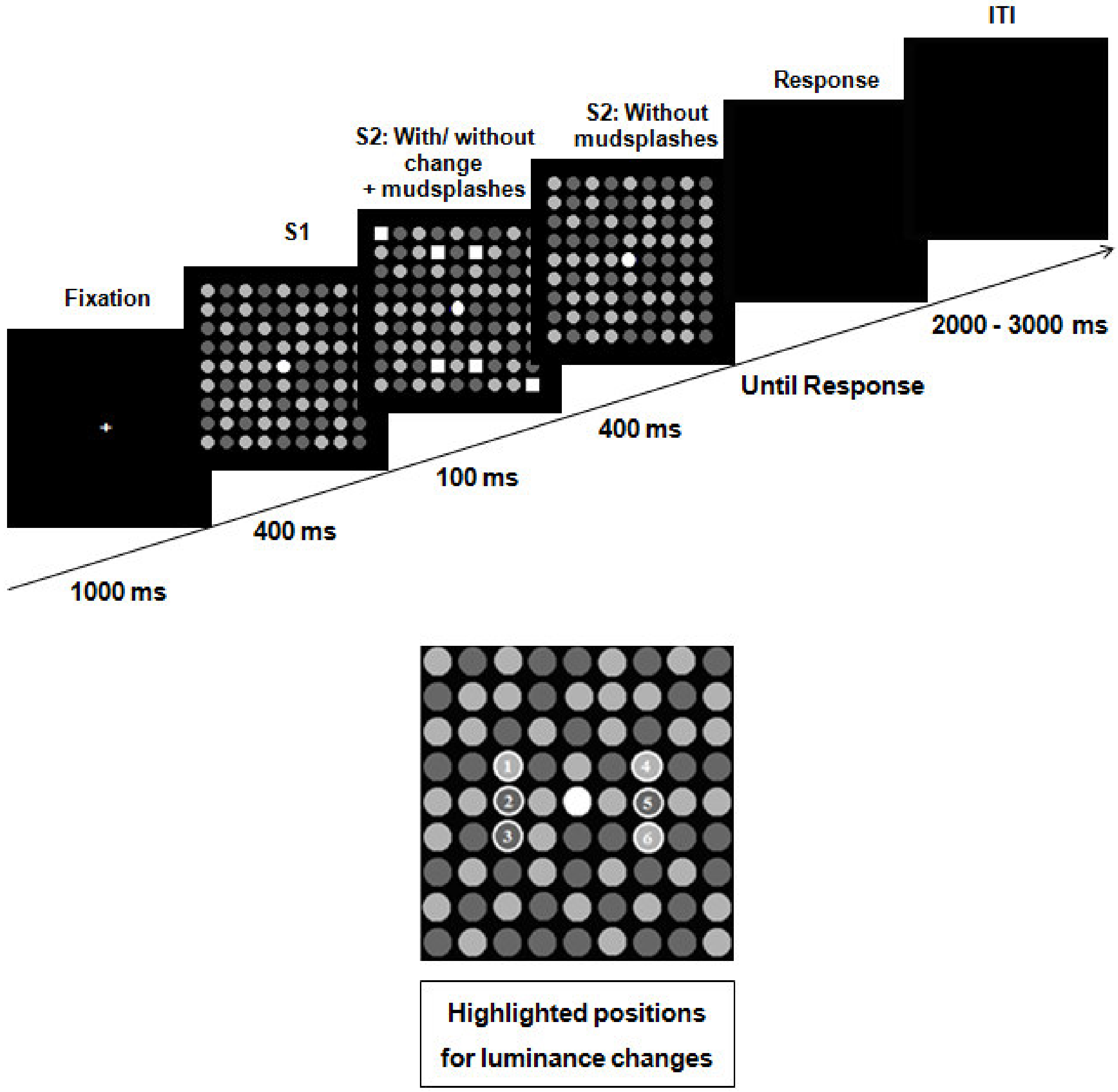

Figure 1. Example for an experimental trial. After a fixation cross (1000ms), matrix S1 appeared (400 ms), then matrix S2 with a possible change (lateral luminance or central color change) followed (100 ms), simultaneously with the mudsplashes. Subsequently, S2 remained on the screen for another 400 ms without the mudsplashes. Afterwards, participants indicated whether they had seen a change or not. Finally an inter-trial interval (ITI) of 2000 – 3000 ms appeared. In this example, six mudsplashes were presented as in the not-highlighted block and in the highlighted-block. In the NUMBER-OF-MUDSPLASHES condition, four or eight mudsplashes appeared in intermingled sequence. The dot in the center of the matrix was colored in either red or green. In the matrix below, the six possible luminance change positions are marked in white color (not visible in the experiment). In the HIGHLIGHTED condition these positions were permanently marked in red color.

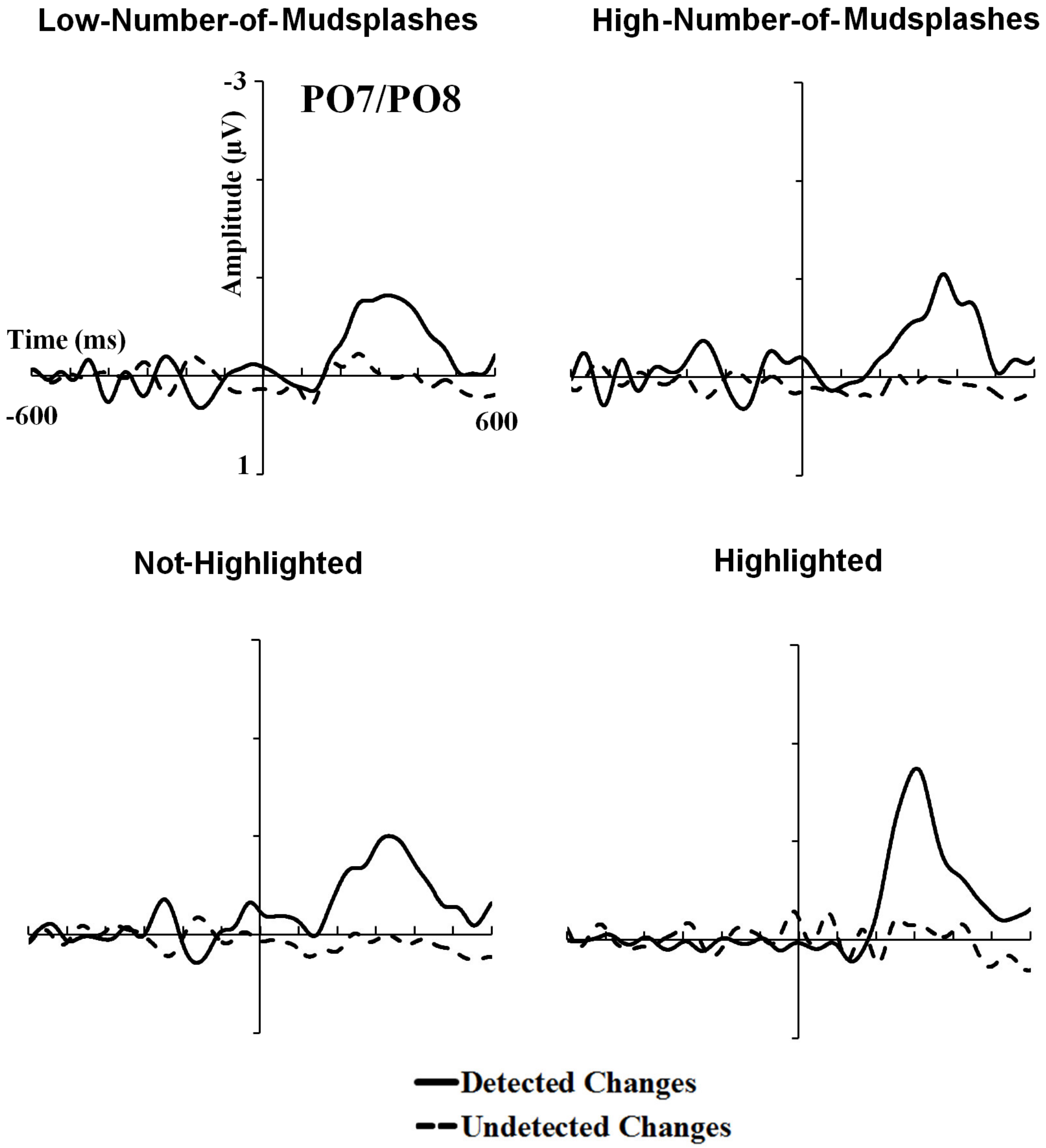

Figure 2. Difference waveforms, separately for the experimental conditions (LOW-NUMBER-OF-MUDSPLASHES, HIGH-NUMBER-OF-MUDSPLASHES, NOT-HIGHLIGHTED, HIGHTLIGHTED). The N2pc was extracted from the ERP by subtracting the ispilateral from the contralateral activity evoked by the onset of the change.

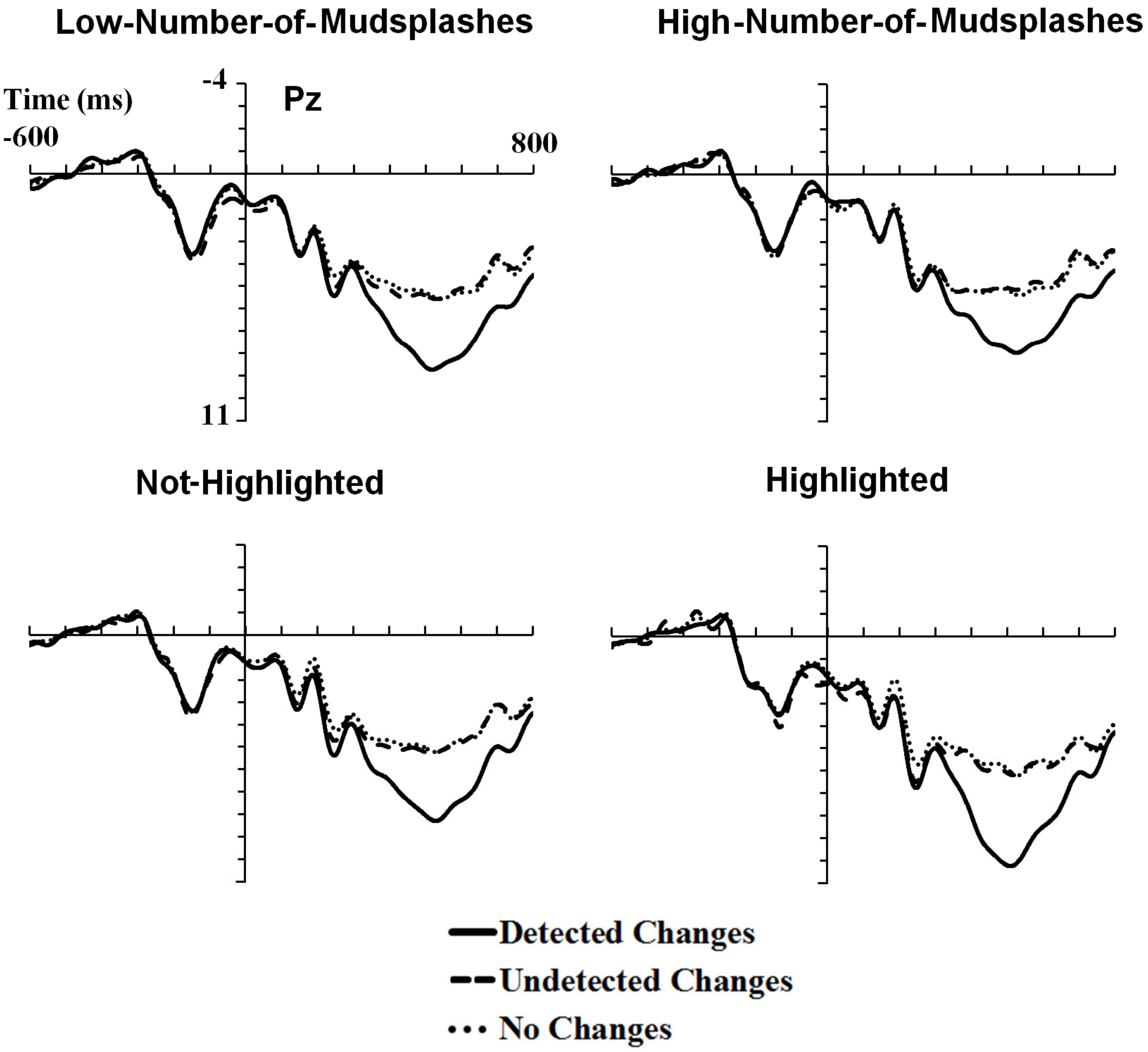

Figure 3. P3 amplitude for detected, undetected, and no changes changes, separately for the experimental conditions (LOW-NUMBER-OF-MUDSPLASHES, HIGH-NUMBER-OF-MUDSPLASHES, NOT-HIGHLIGHTED, HIGHLIGHTED).

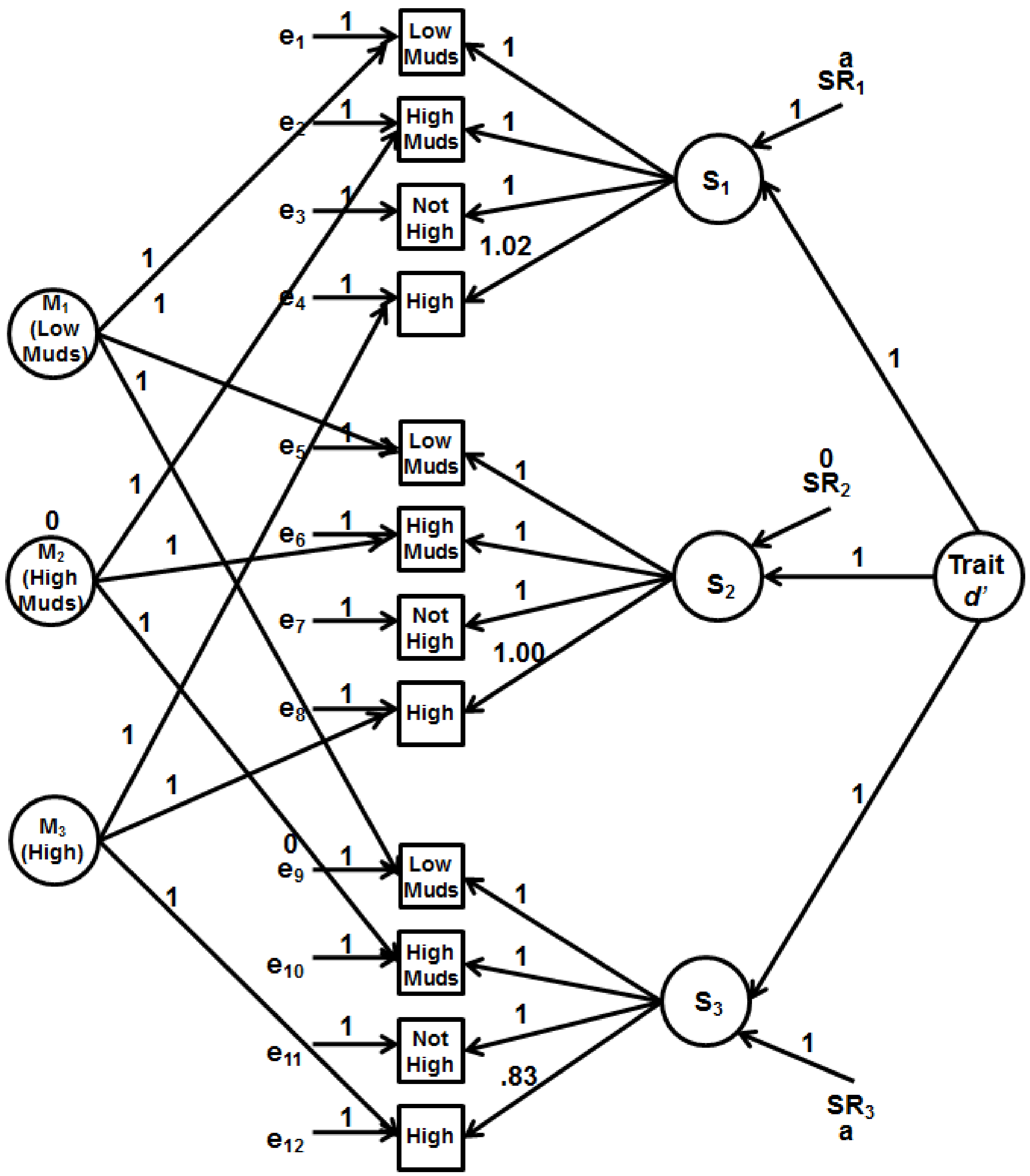

Figure 4. Latent state-trait model for sensitivity *d'*. The variance of the observed variables in the four conditions (Low Muds = LOW-NUMBER-OF-MUDSPLASHES condition, High Muds = HIGH-NUMBER-OF-MUDSPLASHES condition, Not High = NOT-HIGHLIGHTED condition, High = HIGHLIGHTED condition) was decomposed into situation (S_1–S_3), method (M_1–M_3) and measurement error (e). The variance of the situations was decomposed into state residuals (SR_1–SR_3) and into the latent trait (Trait Sensitivity *d'*).

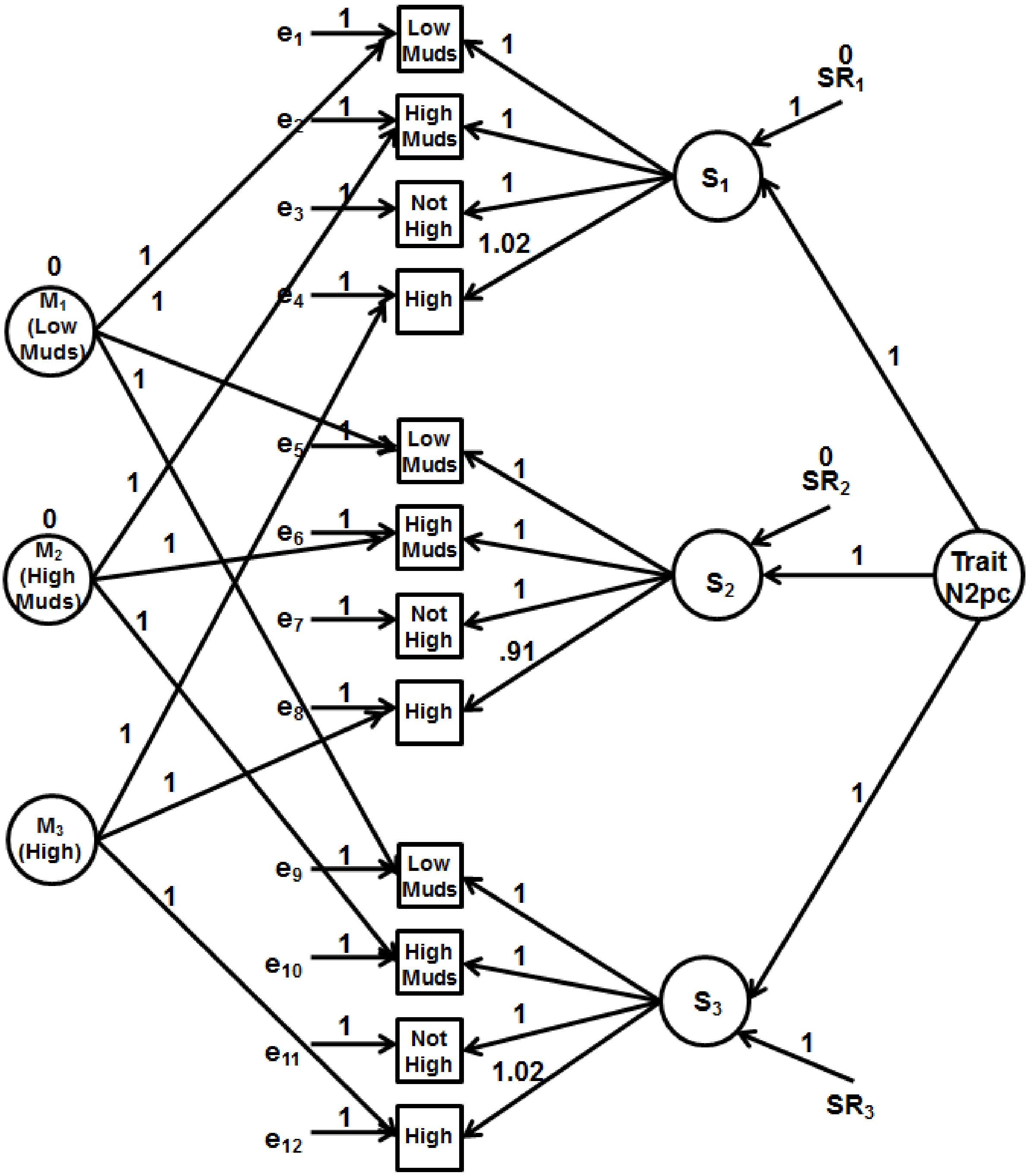

Figure 5. Latent state-trait model for the N2pc amplitude for detected changes. The variance of the observed variables in the four conditions (Low Muds = LOW-NUMBER-OF-MUDSPLASHES condition, High Muds = HIGH-NUMBER-OF-MUDSPLASHES condition, Not High = NOT-HIGHLIGHTED condition, High = HIGHLIGHTED condition) was decomposed into situation (S_1–S_3), method (M_1–M_3) and measurement error (e). The variance of the situations was decomposed into state residuals (SR_1–SR_3) and into the latent trait (Trait N2pc).

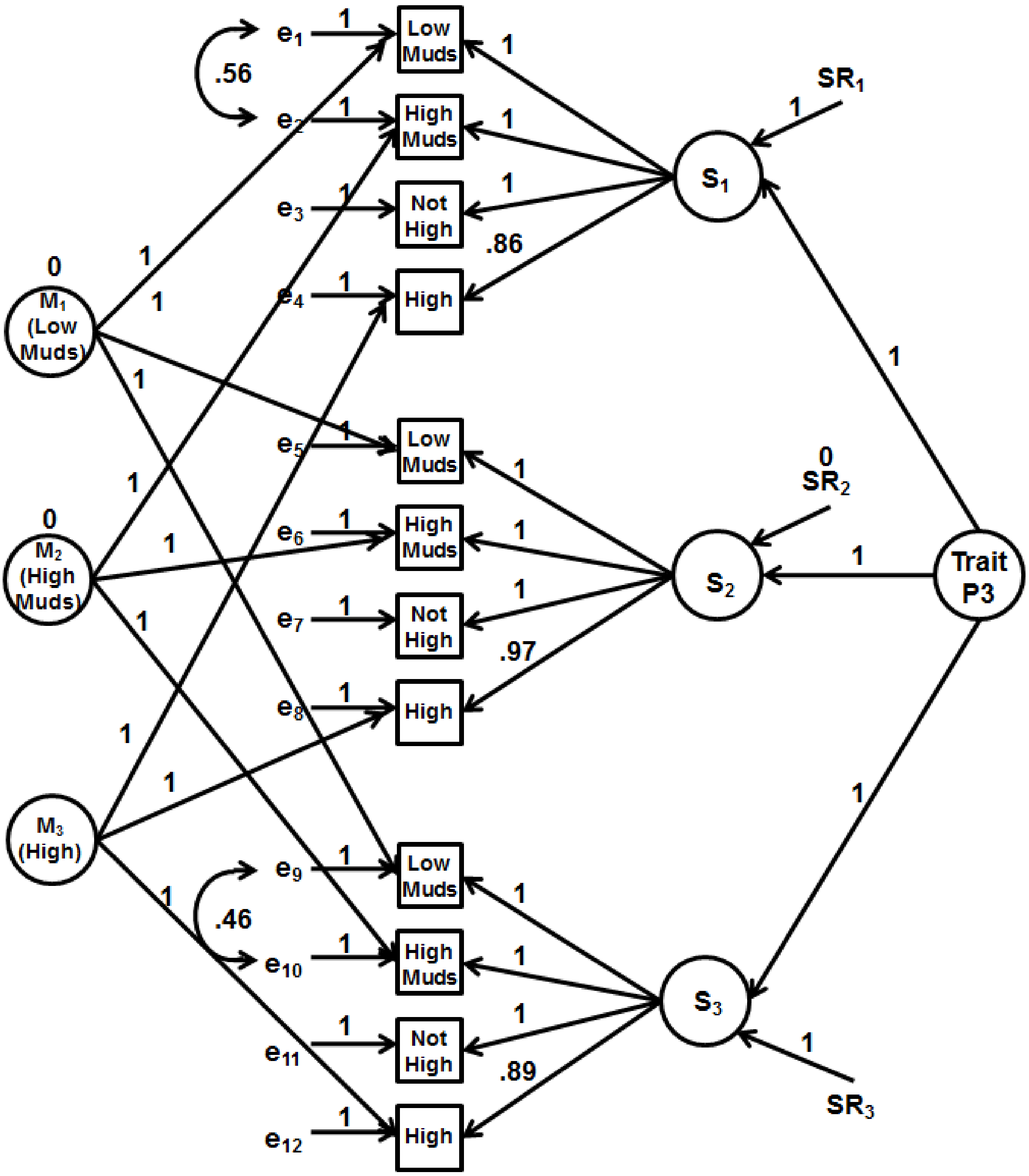

Figure 6. Latent state-trait model for the P3 amplitude for detected changes. The variance of the observed variables in the four conditions (Low Muds = low-number-of-mudsplashes condition, High Muds = HIGH-NUMBER-OF-MUDSPLASHES condition, Not High = NOT-HIGHLIGHTED condition, High = HIGHLIGHTED condition) was decomposed into situation (S_1–S_3), method (M_1–M_3) and measurement error (e). The variance of the situations was decomposed into state residuals (SR_1–SR_3) and into the latent trait (Trait P3).

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AGE-RELATED DIFFERENCES IN THE P3 AMPLITUDE IN CHANGE BLINDNESS

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Abstract

Observers often miss visual changes in the environment when they co-occur with other visual disruptions. This phenomenon is called change blindness. Previous research has shown that change blindness increases with age. The aim of the current study was to explore the role of post-perceptual stimulus processing in age differences. Therefore, the P3 component of the event-related potential was measured while younger, middle-aged, and older participants performed a change detection task under different task demands. Older adults detected fewer changes than younger adults, even when the task was very easy. Detected changes elicited greater P3 amplitudes than undetected changes in younger adults. This effect was reduced or even absent for middle-aged and older participants, irrespective of task demands. Because this P3 effect is supposed to reflect participants' confidence in change detection, less confidence in own responses may explain the decline of change detection performance in normal aging.

Keywords: Change Blindness, Aging, Event-Related Potentials, P3, Post-perceptual Processing, Confidence

Age-related differences on the P3 amplitude in change blindness

Our visual environment consists of an abundance of details. However, we do not perceive all the details of objects and scenes from one view to the next (e.g., Henderson, 1997; Rensink, 2000b). Consequently, it may happen that we do not detect visual changes in a scene – a phenomenon that is known as change blindness (Simons & Levin, 1997). In a typical change blindness experiment an original image is presented, followed consecutively by a slightly different image. This difference usually produces a transient motion signal that attracts observers' attention. When this motion signal is perturbed, e.g. by the presentation of a short blank (Rensink et al., 1997) or by the presentation of mudsplashes (e.g., O'Regan et al., 1999; Schankin & Wascher, 2007, 2008), change blindness may result. This phenomenon is not restricted to figures or photographs in a laboratory setting but may also occur when watching a movie (Simons, 1996) or even in real-life interactions (Simons & Levin, 1998).

There is evidence that older adults perform worse in a change blindness task than younger adults (Rizzo et al., 2009). For example, older participants were less accurate in detecting changes in driving scenes taken from inside a car (Batchelder et al., 2003) or when they were shown photographs of traffic intersections (Caird et al., 2005). The explanations for this age effect are manifold, ranging from deficits in perception, over problems in focusing selective attention to relevant objects, to deficits in tracking and controlling cognitive resources (Batchelder et al., 2003; Caird et al., 2005; Rizzo et al., 2009). For example, older adults may detect fewer changes in driving scenes because they scan more meaningless traffic control devices (e.g., traffic lights) while disregarding meaningful objects (e.g., pedestrians and vehicles; Caird et al., 2005).

Behavioral and neurophysiological studies suggest that evaluative processes play an important role in change detection performance (Rensink, 2000a; Rensink et al., 1997). For the final decision whether or not a change has occurred, the original and the altered image must be encoded, stored in working memory, and compared to each other. The conscious evaluation of this comparison leads to the decision of signaling a change or not (Block, 1996, 1995; Eimer & Mazza, 2005). Theoretically, a change in any or all cognitive processes involved in ongoing decision making may lead to a decline of change detection performance in normal aging.

Neurophysiological methods can be used to identify the cognitive processes involved in a specific task. So far, a broad range of functional neuroimaging studies investigated the change of cognitive processes in normal aging, e.g. in temporal order memory (Cabeza, Anderson, Houle, Mangels, & Nyberg, 2000) in working memory (Johnson, Mitchell, Raye, D'Esposito, & Johnson, 2007; for a review see Hedden & Gabrieli, 2004). Measuring event-related potentials (ERP), however, which allows a high temporal resolution for a more fine-grained analysis of neurocognitive processes, is less common than functional magnet resonance imaging (fMRI) (e.g., Polich, 1996, 1997). It remains disputable, however, which cognitive processes change with age and, thus, lead to a decline of change detection performance with age.

Post-perceptual cognitive processes are reflected by relatively late ERP components. Several studies have shown that successful change detection is reflected by an enhanced P300 or P3 component (e.g., Koivisto & Revonsuo, 2003; L. Li et al., 2013; Niedeggen et al., 2001; Turatto et al., 2002). The P3 is a large positivity peaking about 300 ms after stimulus onset with maximal amplitude at parietal and central midline scalp sites. It has first been described by Sutton et al. (1965) as reaction to an unexpected event. Context or working memory updating is the most common interpretation of its meaning (e.g., Donchin & Coles, 1988; Verleger, 1988). It has been stated that the P3 component reflects a mediating process between perception and response that helps to transform a decision into action (Verleger et al., 2005).

In the context of change detection, O'Connell et al. (2012) investigated the role of the P3 component and the formation of decisions. The ERP showed a single, centro-parietal positivity that was elicited by the gradual onset of a change. It grew in amplitude with accumulating sensory evidence and peaked simultaneously with participants’ response. The authors conclude that this component, which is equal to the P3 component, mirrors a goal-oriented decision process, determined by threshold-bound accumulation of perceptual evidence. Similarily, Koivisto and Revonsuo (2003) suggested that the greater P3 amplitude for detected relative to undetected changes reflects post-perceptual processes of conscious change evaluation. However, the starting level of the perceptual accumulation process might also vary as a function of task demands, stimulus characteristics, or individual differences, such as cognitive aging.

Cognitive aging includes, amongst others, a less efficient working memory, a decreased working memory capacity, and an increased susceptibility to distracting inferences (Dempster, 1992; Dobbs & Rule, 1989). Because these processes play a major role in change detection, elderly might evaluate a change differently than younger participants. However, the effect of aging on post-perceptual cognitive processes has not been investigated in change detection yet. In the current study we use simple visual stimuli in order to measure the electrophysiological brain activity. The main purpose of the present study is to investigate whether age differences in change blindness depend on differences in post-perceptual processes as reflected by the amplitude of the P3 component. Because the P3 amplitude becomes smaller with increasing age across a variety of visual tasks (Fjell & Walhovd, 2003, 2004, 2005; L. Li et al., 2013; Lorenzo-López et al., 2008; for a review see D. Friedman, 2008), this should also be the case in the current study. This effect should be visible particularly in the P3 difference between detected and undetected changes.

Age differences in change blindness may also depend on task demands. Because task demands have an effect on the difficulty of a task, they are supposed to affect the sensitivity for changes. For example, task demands can bias the relevance of a visual change for the observers (Duncan, 1984; O'Regan et al., 2000). As task demands depend on the properties of the perceptual stimulus, such as color (Yu 2010), they can be manipulated by varying the characteristics of stimuli (Pringle et al., 2001). In the current experiment, we varied the number of distracting stimuli (i.e., mudsplashes) or highlighted possible change locations. We propose that fewer distracting mudsplashes as well as highlighted change positions simplify the task and enhance participants' sensitivity for changes. This should be reflected by a larger P3 amplitude (cf. L. Li et al., 2013; Pringle et al., 2001; Verleger, 1988). Moreover, age differences should be more pronounced in highly demanding tasks.

Methods

Participants

Seventy-four paid (8€/hour) volunteers participated in the experiment (38 women, 36 men, age between 18 and 73, mean age 40.1 years). Participants were recruited via newspaper advertisement and web portals. Five participants were left-handed, 61 were right-handed, one was bimanual and seven did not make any entry. When asked for their educational background, one participant indicated to have finished a degree of German lower secondary school, nine participants had an intermediate school leaving certificate, ten a vocational diploma, 19 a German high-school graduation, 31 a university degree, and four a degree of doctorate. Four participants were unemployed, three attended school, nine were students, 39 employees, twelve freelancers, and seven retired. Before the experiment started, participants were informed that it was preconditioned that they were not under psychiatric or neurological treatment. All participants reported normal or corrected to-normal vision and had normal color vision as measured with the Ishihara test of color blindness. Before the experiment started, all of them gave their written informed consent. The study was carried out in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and its amendments.

Participants were divided into three groups on the basis of tertiles: *younger participants* (*N* = 25, 11 women, 14 men, aged between 18 and 29, mean age 25.24 years), *middle-aged* participants (*N* = 24, 11 women, 13 men, aged between 29 and 46, mean age 37.17 years) and *older participants* (*N* = 25, 16 women, 9 men, aged between 47 and 73, mean age 57.64 years).

Apparatus and Stimuli

Participants sat in a comfortable chair in a sound-attenuated chamber, which was dimly lit and electrically shielded. Two keys on a keyboard served as response buttons. The left key was marked in red and the right key in green color. They were located under participants' left and right index finger. Stimuli were presented on a 17-in. computer screen, placed 82 cm in front of them, at the center of their field of vision. The screen was set to a resolution of 1280 x 1024 pixels and a screen refresh rate of 60 Hz.

Stimuli consisted of 81 dots which were arranged in an imaginary 9 x 9 matrix (3.42° x 3.42° of visual angle) and presented on a black background (L = 0, a = 0, b = 0 in a L*a*b color space). Forty of the dots were colored light gray (L = 73, a = 0, b = 0), 40 dots were colored dark gray (L = 42, a = 0, b = 0), and the dot in the center of the matrix was colored either green (L = 34, a = -38, b = 39) or blue (L = 34, a = 58, b = -105). The distance between single dots was .10° and their diameter .28°. The positions of the light and dark gray dots in the matrix were balanced so that accumulations of dots with equal luminance were avoided (cf. Figure 1). In this way, nine matrices were created, which were used for all experimental conditions equally often. In Block 3 light red (L = 73, a = 38, b = 42) and dark red (L = 42, a = 61, b = 55) dots replaced six of the gray dots.

White squares (L = 100, a = 0, b = 0) served as *mudsplashes*, whose number (four, six, or eight) varied between conditions. Each mudsplash (.28° x .28°) occluded exactly one gray dot. The mudsplashes never appeared in immediate vicinity to each other or to a change. Half of the mudsplashes were presented to the left and half to the right visual hemifield. Relative to their distance to the center, they were always presented symmetrically, mirrored along the vertical axis. Fifteen possible arrangements of their spatial positions were constructed in advance and then quasi-randomly ordered per block so that the same arrangement of mudsplashes never appeared more than three times consecutively.

Procedure

Each trial started with a fixation cross in the center of the screen, which lasted 1,000 ms (cf. Figure 1). Afterward, the first matrix (S1) appeared for 400 ms. Then the second matrix (S2) was presented for 100 ms, simultaneously with the mudsplashes. Subsequently, the mudsplashes disappeared and the matrix remained on the screen for another 400 ms. On about 43% of the trials, S1 and S2 were identical (no change trial), on about 43% of the trials, one lateral dot changed its luminance at one of six possible locations (luminance change trial, cf. Figure 1), and on about 14% of all trials, the colored dot in the center changed its color (color change trial). Color changes were used to keep participants' attention fixed to the center of the screen. Trials with color changes were excluded from further analyses because in this condition no change blindness effect can be observed (cf. Schankin and Wascher 2008). Figure 1 shows the three dots of position 1, 2, and 3 (left hemifield) and the three dots of position 4, 5, and 6 (right hemifield). On half of the luminance change trials, the dot changed from dark gray to light gray, on the other half from light gray to dark gray. Similarly, on half of the color change trials, the central dot changed from green to blue, on the other half from blue to green. Finally, an inter-trial interval (ITI) of variable length (2,000 – 3,000 ms) followed.

Participants were instructed to indicate if they had seen a change or not by pressing the green or red key, respectively. The assignment of response keys was counterbalanced across participants. It was stressed that they should report a change only when they really saw it and that guessing was not allowed.

The experiment started with a short demonstration of all possible changes. On each position one exemplary change appeared in slowed presentation time and without any mudsplashes to ensure that all possible changes had been seen once by the participants. Then participants passed 91 practice trials (42 luminance changes, 42 no changes and 7 color changes). In the practice trials, six mudsplashes were presented. The procedure was the same as described above. The practice was followed by Block 1, the *baseline* condition. The procedure was exactly the same as in the practice. Participants were asked to detect a possible luminance change from light gray to dark gray or vice versa at one of six predefined change positions in the matrix. Change blindness was induced by the presentation of six mudsplashes, simultaneously with the change. In Block 2, the number of mudsplashes was varied. Again, participants were asked to detect a possible luminance change from light gray to dark gray or vice versa at six predefined change positions. In contrast to Block 1, either four (*4-mudsplash* condition) or eight mudsplashes (*8-mudsplash* condition) were presented simultaneously with the change. Thus, Block 2 contained two different conditions. In Block 3, possible change positions were permanently marked in red color (*highlighted* condition). Participants were asked to detect a possible luminance change from light red to dark red or vice versa at the same predefined positions as in Block 1 and Block 2. As in Block 1, six mudsplashes were presented. Overall, three blocks that contained four experimental conditions were presented: the baseline condition (Block1, 6 mudsplashes, not-highlighted change positions), the 4-mudsplash condition (Block 2, 4 mudsplashes, not highlighted change positions) in mixed sequence with the 8-mudsplash condition in one block (Block 2, 8 mudsplashes, not highlighted change positions), and the highlighted condition (6-mudsplashes, highlighted change positions) (cf. Table 1).

Each of the four experimental conditions consisted of [4 (color changes) + 12 (luminance changes) + 12 (no changes)] x 9 (matrices) = 252 trials with 108 luminance changes, 108 no changes and 36 color changes each. Altogether, this resulted in 1008 trials per participant.

Within a block, all trials were presented in random sequence with the following constraints. At maximum three luminance changes, three no changes, three changes of the same (left or right) side or two color changes appeared consecutively. Furthermore, the same matrix never appeared more than three times consecutively. In this way, four different trial sequences were created for each block and systematically assigned to participants.

There were always short breaks of individual length after about seven minutes. After each block, there was a longer break.

EEG Recording

EEG was continuously recorded from 25 Ag-AgCl electrodes, placed according to the international 10–20 system. During recording, all electrodes (F3, Fz, F4, T7, C3, C4, T8, TP9, TP10, P7, P3, Pz, P4, P8, PO7, PO8, O1, Oz, O2) were referenced to Cz. Fpz was used as ground. Vertical electro-oculogram (EOG) was recorded bipolarly from above and below the right eye and horizontal EOG from the outer canthi of the eyes. Electrode impedances were kept below 5 kΩ. EEG was sampled with a rate of 1000 Hz. The signal was amplified by two BrainAmp DC amplifiers (Brain Products, Munich, Germany) with a band-pass of 0.1 - 250 Hz. Data was filtered off-line with a band-pass filter of 0.1 – 12 Hz and re-referenced to the average of the mastoid electrodes offline. EEG data were segmented into time windows of 1,700 ms, starting 200 ms prior to S1 and ending 1,400 ms afterward. Baseline was corrected relative to the activity of the interval 200 ms prior to S1 to 0 ms (-600 to -400 ms prior to S2). Ocular artifacts were corrected according to the algorithm of Gratton et al. (1983). Trials with minimum-maximum amplitudes of 100 ms intervals smaller than .5 µV, exceeding +/- 70 µV, or with a voltage step of 100 µV/ms were excluded from the data as artifacts.

Data Analysis

Behavioral Data. We computed hits (percentage of correctly detected luminance changes) and false alarms (percentage of reported changes on no change trials) for each of the four experimental conditions: the baseline condition, the 4-mudsplash condition, the 8-mudsplash condition, and the highlighted condition. To distinguish between differences in sensitivity and response bias, *d'* and *c* were calculated according to the signal detection theory (Green & Swets, 1966). Color changes were excluded from further statistical analyses because in this condition no change blindness effect is observed (cf. Schankin & Wascher, 2008).

Because task demands were manipulated in two ways, two separate statistical analyses were calculated. First, the effect of highlighted change positions was assessed. Therefore, differences between younger, middle-aged, and older adults were analyzed by comparing the baseline condition (Block 1) with the highlighted condition (Block 3). A repeated-measures ANOVA was calculated with the within-subjects factor condition (baseline vs. highlighted condition) and the between-subjects factor age group (younger, middle aged, and older participants) for *d*' or *c*, respectively. Second, the effect of the number of distracting mudsplashes was evaluated. Therefore, differences between younger, middle-aged and older adults were analyzed by comparing the 4-mudsplash condition with the 8-mudsplash condition (Block 2). We run a repeated-measures ANOVA with the within-subjects factor condition (4 vs. 8 mudsplashes; Block 2) and the between-subjects factor age group (younger, middle aged, and older participants) for *d*' or *c*, respectively.

Electrophysiological Data. The P3 amplitude was maximal about 500 ms after change onset (S2) with a maximum at centro-parietal electrodes. For statistical analyses, the P3 amplitude was measured as mean activity in the time window from 400 to 600 ms after change onset. Data from a 3 x 4 electrode grid (F3, Fz, F4; C3, Cz, C4; P3, Pz, P4; O1, Oz, O2) were entered into further statistical analyses. In all conditions participants responded after the P3 time window (mean RT = 1337.15, SD = 403.78). In a few conditions some participants did not detect any changes so that no ERP was recorded for detected changes. These values were indicated as missing in all following analyses.

Again two different statistical analyses were calculated. First, the effect of highlighted change positions was evaluated. Therefore, differences between younger, middle-aged, and older adults were analyzed by comparing the baseline condition (Block 1) and the highlighted condition (Block 3). A repeated-measures ANOVA was calculated with condition (baseline condition vs. highlighted condition; Block 1 vs. Block 3), change type (detected, undetected, and no change), caudality (frontal, central, parietal, and occipital), and laterality (left, middle, and right) as within-subjects factor and age group (younger, middle-aged, and older participants) as between-subjects factor. Second, to test for age differences when task demands were manipulated by varying the number of distracting mudsplashes, we performed a repeated-measures ANOVA with condition (4 vs. 8 mudsplashes; Block 2), change type (detected, undetected, and no change), caudality (frontal, central, parietal, and occipital), and laterality (left, middle, and right) as within-subjects factor and age group (younger, middle-aged, and older participants) as between-subjects factor. Only effects involving the factors age group, change type, and condition are reported. For the analysis of general topographic age differences, we focused on the three- and four-way interaction of age group, change type, and caudality and / or laterality.

All statistics were adjusted by Greenhouse-Geisser epsilon correction for nonsphericity if the number of factor levels exceeded two. In this case, uncorrected degrees of freedom but corrected p values are reported. If indicated, additional post hoc analyses were calculated. In case of multiple comparisons, p was adjusted according to Bonferroni.

To assess the linear effect of age on change detection, we computed correlations separately for each experimental condition (i.e., baseline condition, 4-mudsplash condition, 8-mudsplash condition, and highlighted condition). The relationships between participants' age, their sensitivity for changes *d*', and effects of post-perceptual cognitive processes as reflected by the P3 amplitude (i.e., the amplitude difference between detected and undetected changes) were analyzed. These analyses were restricted to electrode Pz because the effect of change blindness on the P3 amplitude was most pronounced at this electrode site.

Results

Age had a substantial effect on behavioral and electrophysiological data. Younger, middle-aged, and older participants' accuracy rates for luminance changes and no changes are displayed in Table 1. Mean values of sensitivity *d*' and response bias *c* are presented in Figure 2. Grand averages of event-related potential waveforms for younger, middle-aged, and older participants are exemplarily shown at electrode Fz (Figure 3), Cz (Figure 4), and Pz (Figure 5). Figure 6 shows the topographical maps for detected and undetected changes, separately for each experimental condition.

Highlighted Change Positions

In a first analysis, task demands were assessed by comparing the baseline condition with the highlighted condition.

Behavioral Data. In the baseline condition participants responded correctly to 27.9% (standard error of mean = 2.3%) of the luminance changes and to 90.4% (standard error of mean = 1.1%) of the no changes. In the highlighted condition participants responded correctly to 74.1% (standard error of mean = 2.9%) of the luminance changes and to 94.7% (standard error of mean = 1.3%) of the no changes.

Age Effects. We found a significant main effect of age group on sensitivity *d'*, $F(2,71) = 19.4$, $p < .001$, $\omega^2 = .341$. Post hoc tests indicated that younger and middle-aged participants did not differ in their sensitivity for changes, $F(1,47) = 3.7$, $p = .183$, $\omega^2 = .054$, whereas younger participants $F(1,48) = 35.7$, $p < .001$, $\omega^2 = .420$, as well as middle-aged participants, $F(1,47) = 20.8$, $p < .001$, $\omega^2 = .296$, were more sensitive to changes than older participants. The interaction of age group and condition was significant, $F(2,71) = 3.2$, $p = .048$, $\omega^2 = .058$. In the baseline condition younger participants, $F(1,48) = 28.4$, $p < .001$, $\omega^2 = .363$, and middle-aged participants, $F(1,47) = 11.2$, $p = .006$, $\omega^2 = .178$, were more sensitive to changes than older participants. The difference between younger and middle-aged participants was marginally significant, $F(1,47) = 5.0$, $p = .090$, $\omega^2 = .078$. As in the baseline condition younger participants $F(1,48) = 30.7$, $p < .001$, $\omega^2 = .382$, and middle-aged participants, $F(1,47) = 20.8$, $p < .001$, $\omega^2 = .296$, were more sensitive to changes than older participants in the highlighted condition. However, the difference between younger and middle-aged participants did not reach significance, $F(1,47) = 1.7$, $p = .594$, $\omega^2 = .015$.

The response bias c did not differ significantly between age groups, $F(2,71) = 2.0$, $p = .138$, $\omega^2 = .027$. The interaction of age group and condition was significant, $F(2,71) = 5.0$, $p = .009$, $\omega^2 = .101$. In the highlighted condition the response bias c did not differ between younger and middle-aged participants, $F(1,47) < 1.0$, whereas older participants responded more conservatively than younger participants, $F(1,48) = 8.4$, $p = .018$, $\omega^2 = .134$, and more conservatively than middle-aged participants, $F(1,47) = 10.4$, $p = .006$, $\omega^2 = .167$. In the baseline condition, however, the main effect of response bias did not reach significance, $F(2,71) < 1.0$.

Further Statistical Effects. Participants were more sensitive to changes in the highlighted condition than in the baseline condition, $F(1,71) = 642.4$, $p < .001$, $\omega^2 = .900$. Furthermore, participants responded more conservatively in the baseline condition than in the highlighted condition. $F(1,71) = 67.5$, $p < .001$, $\omega^2 = .484$.

Electrophysiological Data. Age differences in change blindness should also be visible in the ERP.

Age Effects. The main effect of age group on the P3 amplitude did not reach significance, $F(2,69) = 1.1$, $p = .345$, $\omega^2 = .003$ (cf. Figure 5). Participants' age group and the type of change (detected, undetected, and no changes) interacted with one another, $F(4,138) = 5.6$, $p = .001$, $\varepsilon = .872$, $\omega^2 = .118$. The effect of change type on the P3 amplitude was most pronounced in younger participants, $F(2,48) = 38.8$, $p < .001$, $\varepsilon = .991$, $\omega^2 = .612$, smaller but also present in older participants, $F(2,46) = 13.0$, $p < .001$, $\varepsilon = .708$, $\omega^2 = .343$, whereas it was absent in middle-aged participants, $F(2,44) = 1.1$, $p = .981$, $\varepsilon = .802$, $\omega^2 = .005$.

Participants' age group and the experimental condition did not interact with each other, $F(2,69) = 1.6$, $p = .214$, $\omega^2 = .017$. The three-way interaction of age group with change type and condition was not significant, $F(4,138) < 1.0$.[1]

Furthermore, we observed a significant three-way interaction of change type with caudality and age group, $F(12,414) = 2.8$, $p = .017$, $\varepsilon = .453$, $\omega^2 = .050$. In younger participants, the effect of change type was most pronounced at parietal electrode sites, $F(2,48) = 51.7$, $p < .001$, $\varepsilon = .975$, $\omega^2 = .679$, though it was present at all other electrode lines (frontal: $F(2,48) = 5.0$, $p = .044$, $\varepsilon = .995$, $\omega^2 = .143$; central: $F(2,48) = 27.1$, $p < .001$, $\varepsilon = .971$, $\omega^2 = .521$; and occipital: $F(2,48) = 30.3$, $p < .001$, $\varepsilon = .935$, $\omega^2 = .550$). The interaction was absent in middle-aged and older participants, all Fs ≤ 1.9, all ps $\geq .525$.

Moreover, the three-way interaction of change type with laterality and age group reached significance as well, $F(8,276) = 2.5$, $p = .023$, $\varepsilon = .766$, $\omega^2 = .042$. In older participants, the effect of change type was most pronounced at right electrode sites, $F(2,46) = 14.8$, $p < .001$, $\varepsilon = .738$, $\omega^2 = .375$, but it was also present at midline electrodes, $F(2,46) = 14.0$, $p < .001$, $\varepsilon = .666$, $\omega^2 = .361$, and left electrode sites, $F(2,46) = 7.6$, $p = .012$, $\varepsilon = .727$, $\omega^2 = .223$. The interaction was absent in younger and middle-aged participants, all $Fs \leq 2.7$, all ps $\geq .228$.

Further Statistical Effects. We observed a significant main effect of change type, $F(2,138) = 32.6$, $p < .001$, $\varepsilon = .872$, $\omega^2 = .314$. Post hoc tests showed that the P3 amplitude was enhanced for detected changes compared to no changes, $F(1,72) = 49.8$, $p < .001$, $\omega^2 = .404$, and to undetected changes, $F(1,71) = 27.9$, $p < .001$, $\omega^2 = .275$, but no difference was found between no changes and undetected changes, $F(1,72) = 2.3$, $p = .399$, $\omega^2 = .018$. Furthermore, the P3 amplitude was larger in the highlighted condition than in the baseline condition, $F(1,69) = 21.4$, $p < .001$, $\omega^2 = .228$. The interaction of change type with condition was significant as well, $F(2,138) = 10.3$, $p < .001$, $\varepsilon = .869$, $\omega^2 = .119$. This effect was more pronounced in the highlighted condition, $F(2,144) = 48.4$, $p < .001$, $\varepsilon = .866$, $\omega^2 = .397$. However, it was also present in the baseline condition, $F(2,144) = 4.3$, $p = .033$, $\varepsilon = .636$, $\omega^2 = .044$.

Correlational Analysis. Age and sensitivity *d'* were negatively correlated in the baseline condition, $r = -.52$, $p < .001$, and in the highlighted condition, $r = -.59$, $p < .001$. Furthermore, the correlation of *d'* and the P3 amplitude (detected minus undetected changes) reached marginal significance in the highlighted condition, $r = .20$, $p = .087$, but not in the baseline condition, $r = .18$, $p = .118$. We observed a significant negative relationship of age and the P3 amplitude in the highlighted condition, $r = -.36$, $p = .002$, whereas it was only marginally significant in the baseline condition, $r = -.21$, $p = .081$.

Number of Mudsplashes

In a second analysis, we manipulated task demands by varying the number of irrelevant mudsplashes in Block 2.[2]

Behavioral Data. In the 4-mudsplash condition participants responded correctly to 32.8% (standard error of mean = 2.8%) of the luminance changes and to 95.1% (standard error of mean = .1%) of the no changes. In the 8-mudsplash condition they were correct on 24.7% (standard error of mean = 2.3%) of the luminance changes and on 94.4% (standard error of mean = .7%) of the no changes.

Age Effects. We found a significant main effect of age group on sensitivity *d'*, $F(2,71) = 10.2$, $p < .001$, $\omega^2 = .206$. Post hoc tests indicated that younger participants responded marginally more sensitive to changes than middle-aged participants, $F(1,47) = 5.6$, $p = .066$, $\omega^2 = .089$, and older participants, $F(1,48) = 20.1$, $p < .001$, $\omega^2 = .285$, whereas middle-aged participants did not differ in their sensitivity from older participants, $F(1,47) = 4.8$, $p = .126$, $\omega^2 = .075$. The interaction of age group and condition was not significant, $F(1,71) < 1.0$.

The response bias *c* did not differ significantly between age groups, $F(2,71) = 2.1$, $p = .129$, $\omega^2 = .030$. The interaction of age group and condition did not reached significance, $F(2,71) < 1.0$.

Further Statistical Effects. Participants were more sensitive to changes in the 4-mudsplash condition than in the 8-mudsplash condition, $F(1,71) = 35.4$, $p < .001$, $\omega^2 = .326$. Furthermore, they responded more conservatively in the 8-mudsplash condition than in the 4-mudsplash condition, $F(1,71) = 9.5$, $p = .003$, $\omega^2 = .107$.

Electrophysiological Data. These age differences in change blindness should also be observable in the ERP.

Age Effects. The main effect of age group on the P3 amplitude did not reach significance, $F(2,67) < 1.0$. (cf. Figure 5). Participants' age and the type of change (detected, undetected, and no changes) interacted with one another, $F(4,134) = 7.9$, $p < .001$, $\varepsilon = .667$, $\omega^2 = .171$. Post hoc tests showed that the effect of change type was most pronounced in younger participants, $F(2,48) = 15.4$, $p < .001$, $\varepsilon = .672$, $\omega^2 = .375$, but it was also observable in middle-aged participants, $F(2,42) = 8.3$, $p < .001$, $\varepsilon = .785$, $\omega^2 = .258$, whereas it was absent in older participants, $F(2,44) < 1.0$.

Participants' age group and the experimental condition did not interact with each other, $F(2,67) < 1$. The three-way interaction of age group with change type and condition was not significant, $F(4,134) = 1.5$, $p = .218$, $\varepsilon = .953$, $\omega^2 = .015$.[3]

Furthermore, we observed a significant three-way interaction of change type with caudality and age, $F(12,402) = 2.9$, $p = .036$, $\varepsilon = .269$, $\omega^2 = .054$. In younger participants, the effect of change type was most pronounced at parietal electrodes, $F(2,48) = 21.1$, $p < .001$, $\varepsilon = .669$, $\omega^2 = .456$, but it was also present at all other electrode lines (frontal: $F(2,48) = 6.2$, $p = .040$, $\varepsilon = .719$, $\omega^2 = .178$; central: $F(2,48) = 12.2$, $p < .001$, $\varepsilon = .685$, $\omega^2 = .318$; and occipital: $F(2,48) = 15.1$, $p < .001$, $\varepsilon = .607$, $\omega^2 = .370$). The interaction of change type and caudality did not reach significance in middle-aged participants, $F(6,126) < 1.0$, and in older participants, $F(6,132) = 1.7$, $p = .368$, $\varepsilon = .402$, $\omega^2 = .031$.

Moreover, a significant three-way interaction of change type with laterality and age group was found. In younger participants, the effect was most pronounced at midline electrodes, $F(2,48) = 17.1$, $p < .001$, $\varepsilon = .629$, $\omega^2 = .401$, though it was also present for right electrode sites, $F(2,48) = 14.1$, $p < .001$, $\varepsilon = .689$, $\omega^2 = .353$, and left electrode sites, $F(2,48) = 13.3$, $p < .001$, $\varepsilon = .717$, $\omega^2 = .339$. The interaction was absent in middle-aged and older participants, all $Fs \leq 3.2$, all ps $\geq .105$.

Further Statistical Effects. The P3 amplitude differed significantly between detected, undetected, and no changes, $F(2,134) = 13.0$, $p < .001$, $\varepsilon = .667$, $\omega^2 = .152$. Post hoc tests showed that the P3 amplitude was enhanced for detected changes compared to no changes, $F(1,67) = 13.4$, $p < .001$, $\omega^2 = .156$, and to undetected changes, $F(1,67) = 15.1$, $p < .001$, $\omega^2 = .167$, but no difference was found between no changes and undetected changes,

$F(1,71) = 2.1$, $p = .465$, $\omega^2 = .015$. Furthermore, The P3 amplitude was larger in the 4-mudsplash condition than in the 8-mudsplash condition, $F(1,67) = 10.1$, $p = .002$, $\omega^2 = .120$. The interaction of change type with condition was significant as well, $F(2,134) = 4.5$, $p = .014$, $\varepsilon = .953$, $\omega^2 = .005$. This effect was more pronounced in the 4-mudsplash condition, $F(2,140) = 9.9$, $p = .001$, $\varepsilon = .675$, $\omega^2 = .113$, but it was also present in the 8-mudsplash condition, $F(2,142) = 6.2$, $p = .007$, $\varepsilon = .717$, $\omega^2 = .068$.

Correlational Analysis. Sensitivity d' and age were negatively correlated in the 4-mudsplash condition, $r = -.43$, $p < .001$, and in the 8-mudsplash condition, $r = -.50$, $p < .001$. Furthermore, d' and the P3 amplitude (detected minus undetected changes) were correlated in the 4-mudsplash condition, $r = .39$, $p = .001$, and in the 8-mudsplash condition, $r = .39$, $p = .001$. Furthermore, we observed a negative relationship of age and the P3 amplitude in the 4-mudsplash condition, $r = -.29$, $p = .017$, and in the 8-mudsplash condition, $r = -.53$, $p < .001$.

Discussion

Previous research has shown that older adults detect fewer changes in change blindness tasks than younger adults (e.g., Costello et al., 2010). We wanted to investigate whether this age difference in change detection performance may rely on differences in post-perceptual cognitive processes. If this were the case, the effect should be reflected by the P3 component of the ERP as an electrophysiological correlate of late cognitive stimulus processing (e.g., Donchin & Coles, 1988; Koivisto & Revonsuo, 2003; Verleger, 1988). Change blindness was induced by mudsplashes presented simultaneously with the change (cf. O'Regan et al., 1999). Because age differences might be modulated by the demands of a task, the number of distracting stimuli (i.e., mudsplashes) was varied or possible change locations were highlighted, respectively. We hypothesized that task demands are higher with a larger number of mudsplashes and become lower when change positions are highlighted. Age effects in the P3 amplitude should become visible in particular when task demands are high. When task demands are low, however, we expected to find small or no age differences. It should be stressed that we, in contrast to most previous aging studies, included a group of middle age to analyze a trajectory of age effects in the current study.

In line with previous research (e.g., Costello et al., 2010), younger adults were more sensitive to changes than older adults. Importantly, younger and middle-aged participants did not differ in their sensitivity for changes. That is, a decrease in change detection performance came into effect only in older age. This is in accordance with former research, which showed that the sensitivity for changes begins to decline at about 68 years (Rizzo et al., 2009). Electrophysiologically, this effect was not reflected by the mean amplitude of the P3 component, i.e., there was no general decline in the P3 amplitude with age when averaged across detected, undetected, and no changes. Statistically, the main effect of age group in any analyses was insignificant, with negligible small effect sizes close to zero. That is, a general change in post-perceptual cognitive processes that are reflected by the averaged P3 amplitude, like working memory updating (e.g., Verleger, 1988), cannot explain the effect of age on the sensitivity for changes. This finding seems to contradict most previous studies, which report a decrease in the P3 amplitude with age, e.g. in visual search (e.g., L. Li et al., 2013; Lorenzo-López et al., 2008). It has to be mentioned, however, that a few studies found similar or even increased amplitudes for older adults compared to younger adults (Daffner, Alperin, Mott, & Holcomb, 2014; Fabiani, 2012; Wiegand et al., 2014). In these studies, the amplitude of the P3 component was dependent on the experimental paradigm, on task requirements (Daffner et al., 2011; Daffner et al., 2014; Luck, 2005), or on individuals' performance (Daffner et al., 2011). Daffner et al. (2011) even observed increased P3 amplitudes for older adults compared to younger adults although both groups showed the same performance in a working memory task. These larger amplitudes were explained by a compensation mechanism in older adults.

Thus, further cognitive processes may contribute to age differences in change detection and change blindness. One promising candidate is the spatial allocation of selective attention – a process that is necessary for successful change detection (e.g., Eimer & Mazza, 2005; Rensink et al., 1997; O'Regan et al., 1999; Schankin & Wascher, 2007, 2008). Electrophysiologically, attentional processes are reflected by the N2 and N2pc component in the ERP, which peak about 200 to 300 ms after stimulus onset at posterior electrode sites. If attention played an important role in explaining age differences in a change detection task, this should be reflected by the N2 or N2pc component. This was indeed the case in a recent change blindness study by Wascher et al. (2012). The authors reported enhanced amplitudes of the N2pc component toward more salient changes in older adults. In contrast, the effect in the N2 amplitude was not affected by age. According to the authors, older adults seem to have more difficulties in maintaining an intentional allocation of attention toward relevant characteristics of the stimuli than younger adults, whereas the executive control of attention does not change with age.

Previous research has shown that detected changes elicit greater P3 amplitudes than undetected changes (e.g., Eimer & Mazza, 2005; Koivisto & Revonsuo, 2003; Schankin & Wascher, 2007; Turatto et al., 2002). This was also the case in the present experiment. The enlarged positivity for detected changes has been interpreted as reflecting the aware identification of the change (Niedeggen et al., 2001) or post-perceptual mechanisms necessary for decision making or action planning, e.g. the formation of the decision per se (O'Connell et al., 2012).

The size of this change blindness effect in the P3 amplitude, i.e. the difference between detected and undetected (or no) changes, depended on age: The effect was greater in younger participants in comparison to middle-aged and older participants. It should be stressed that this electrophysiological finding only partly fits to the behavioral data. Behaviorally, the sensitivity for changes began to decline not before older age, whereas the P3 effect was already observable in middle-aged participants. We suppose that during lifetime, the decrease of the P3 amplitude begins before it is observable in participants' behavior. Importantly, the negative relation between age and the P3 amplitude was not consistently found in all experimental conditions, but depended on task demands (see below for a discussion). Thus, the interpretation of the P3 effect as reflecting an aware identification of the change or processes necessary for the report of a change do not fit the data very well.

Alternatively, it has been suggested by Eimer and Mazza (2005) that the P3 reflects observers' confidence in the presence or absence of a change. In their change blindness experiment, one of four faces could change its identity across displays. Participants were asked to indicate their subjective confidence regarding the presence of a change at the end of each trial. The P3 amplitude did not differ between detected and undetected changes when participants were low in confidence. When participants were high in confidence, however, the P3 was enhanced in detected compared to undetected changes. According to the authors, confidence but not change detection was the underlying cause for an increase in the P3 amplitude. This interpretation is in accordance with the finding that older adults are less overconfident with respect to their own ratings than younger adults, e.g. in knowledge tests (Kovalchik, Camerer, Grether, Plott, & Allman, 2005; Pliske & Mutter, 1996). In the current experiment younger participants might have been more confident in reporting a change than middle-aged or older participants.

Finally, the topography of the P3 effect changed with age. In younger participants, the P3 effect of change detection versus change blindness was most pronounced at parietal and midline electrodes. This finding is in accordance with other studies (D. Friedman, Kazmerski, & Fabiani, 1997a; Polich & Heine, 1996). In older adults, however, the activation was stronger over the right hemisphere. This change in distribution has been observed before (e.g., Daffner et al., 2011; Wiegand et al., 2014). It has been interpreted as being indicative for a stronger reliance on executive control processes, which are helpful in storing information in working memory (e.g., Fjell & Walhovd, 2001; Wiegand et al., 2014). In a change blindness task, older adults could shift their search strategy and attempt to compensate, e.g. sensory deficits that would otherwise reduce change detection performance. This assumption is confirmed by a part of our analyses. Older adults responded more conservatively than younger and middle-aged participants, in particular when the task became easier in the highlighted condition. This observation is in line with previous research that has shown that aging goes along with a more cautious response strategy (L. Li et al., 2013; Rizzo et al., 2009). This finding could also be related to a decrease in participants' confidence in their own ratings. However, the relationship between confidence and response bias needs to be examined in future research.

A second aim of the current study was to investigate whether age differences in change detection performance are modulated by task demands. Age differences may become greater when task demands are high. Therefore, two further experimental conditions were introduced. First, the number of mudsplashes was varied to investigate the influence of irrelevant stimuli. As expected, more changes were detected when four mudsplashes were presented compared to eight mudsplashes, i.e. the task became easier. Second, possible change locations were highlighted by permanently marking them in red color. In comparison to the baseline condition participants detected more changes when change locations were marked. In all conditions, older participants detected fewer changes than younger ones. In contrast to our predictions, this age difference was visible in particular when change positions were highlighted, i.e. when task demands were lowest. We suppose that older adults benefited less from highlighting change positions than middle-aged or younger adults, possibly due to difficulties in the intentional allocation of attention toward the change (cf. Wascher et al., 2012), but further research is necessary to test this hypothesis.

Electrophysiologically, task demands were reflected by the P3 amplitude. The easier the task became, the more the amplitude of the P3 increased, with the largest amplitude in the highlighted condition. This finding is in accordance with former studies that reported an increase in the P3 amplitude for less demanding tasks (e.g., Verleger, 1988). The effect of task demands on the P3 amplitude was not modulated by participants' age, i.e. post-perceptual processes were modulated by task demands similarly in younger and older adults.

Before strong conclusions might be drawn, some limitations of the current experiment have to be considered. First, one may argue that age differences might simply be caused by a rising sensory deficit with age. For example, older adults have a reduced useful field of view (UFOV), i.e. the visual area in which information can be gathered when eyes are fixated (Ball, Beard, Roenker, Miller, & Griggs, 1988; Rizzo et al., 2009). A smaller UFOV might hinder the successful evaluation of the change and thus indirectly affect the size of participants' P3 amplitude. In the present study, however, a smaller UFOV can be excluded as a cause of age differences in sensitivity because all to-be-detected changes were presented within a critical cutoff point of 40° of visual angle (Ball, Beard, Roenker, Miller, & Griggs, 1993).

Second, the sequence of the experimental conditions could have influenced the results. All participants started the experiment with the baseline condition (Block 1), followed by the 4-mudsplash and 8-mudsplash condition (Block 2), and finished with the highlighted condition (Block 3). That is, the sequence of the three different blocks is confounded with practice or fatigue, which both might have an effect on the sensitivity for changes. Indeed, the sensitivity for changes was significantly greater in Block 3 than Block 1. This result might be due to practice, at least to a certain extend. It has also taken into account that in the ongoing course of the experiment older and middle-aged adults probably had more difficulties in maintaining a vigilant state than younger ones (e.g., Deaton & Parasuraman, 1993), possibly due to increased mental fatigue (cf. Boksem, Meijman, & Lorist, 2005). It cannot be excluded that these processes and their interactions have influenced participants' sensitivity for changes, the confidence in their own rating, and thus the size of the P3 amplitude. In Block 2, however, four and eight mudsplashes were presented in mixed sequence. Therefore, effects of practice and fatigue can be excluded in this comparison.

Third, the findings on the P3 amplitude suggest that confidence might be one of the key variables explaining the decline in change detection performance in normal aging. To strengthen this interpretation, individual confidence ratings need to be measured in future aging studies on change blindness. For example, Eimer and Mazza (2005) asked their participants to indicate after each trial how confident they felt in their own response with regard to the presence of a change.

Despite these limitations, the current experiment shows that post-perceptual processes change with age. In particular, the confidence in the presence of a visual change explains why older adults report fewer changes than younger or middle-aged adults. Interestingly, differences in confidence begin to occur in midlife, whereas change detection performance begins to decline not before older age. Further cognitive processes might contribute to an age-related decline in change detection performance, e.g. the allocation of visual-spatial attention (Wascher et al., 2012). Possibly, compensation mechanisms or participants' search strategies also play a major role here.

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Ethical Standards

All human studies have been approved by the appropriate ethics committee and have therefore been performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and its later amendments. All persons gave their informed consent prior to their inclusion in the study. Details that might disclose the identity of the subjects under study were omitted. The manuscript does not contain clinical studies or patient data.

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Footnotes

[1] An analysis with extreme age groups, i.e., with the outer quartiles of the age distribution ($N = 19$ per age group), yielded similar results: When highlighted change positions were analyzed, the main effect of age group did not reach significance, $F(1,35) < 1.0$. Participants' age group and the type of change (detected, undetected, and no changes) interacted with one another, $F(2,70) = 7.5$, $p = .002$, $\varepsilon = .921$, $\omega^2 = .157$. Participants' age group and the experimental condition did not interact with each other, $F(1,35) = 1.3$, $p = .257$, $\omega^2 = .008$. The three-way interaction of age group with change type and condition was not significant, $F(2,70) < 1.0$.

[2] In this analysis we only compare the 4-mudsplash condition with the 8-mudsplash condition (both presented in Block 2), but did not include the 6-mudsplash (presented in Block 1), to avoid a confound between the number of mudsplashes with the way of presentation. Because in Block 2 the 4-mudsplash and the 8-mudsplash condition were presented mixed together, i.e., the number of mudsplashes was not predictable from trial to trial, task demands increased in general and participants' uncertainty might be higher than in Block 1.

[3] Similar results were found when the number of mudsplashes was analyzed with extreme age groups, i.e., with the outer quartiles of the age distribution ($N = 19$ per age group). The main effect of age group did not reach significance, $F(1,34) = 1.0$. Participants' age group and the type of change (detected, undetected, and no changes) interacted with one another, $F(2,68) = 13.0$, $p < .001$, $\varepsilon = .619$, $\omega^2 = .261$. Participants' age group and the experimental condition did not interact with each other, $F(1,34) < 1.0$. The three-way interaction of age group with change type and condition was not significant, $F(2,68) = 1.1$, $p = .336$, $\varepsilon = .999$, $\omega^2 = .003$.

Tables

Table 1. Mean accuracy rate in percentage (standard error of mean) as a function of condition and age.

	Block	**Stimulation**	**No Change**	**Luminance Change**
Younger Participants	Block 1	6 Mudsplashes	90.4 (1.0)	35.4 (5.0)
	Block 2	4 Mudsplashes	95.1 (.8)	45.0 (5.4)
		8 Mudsplashes	94.4 (.9)	34.2 (4.7)
	Block 3	Highlighted	94.7 (.8)	85.5 (3.8)
Middle-aged Participants	Block1	6 Mudsplashes	90.1 (2.0)	27.3 (3.4)
	Block2	4 Mudsplashes	95.1 (.9)	32.9 (4.7)
		8 Mudsplashes	94.1 (1.2)	23.7 (3.6)
	Block3	Highlighted	92.0 (3.7)	82.4 (2.8)
Older Participants	Block1	6 Mudsplashes	85.9 (2.2)	21.1 (2.8)
	Block2	4 Mudsplashes	93.6 (1.6)	20.1 (2.9)
		8 Mudsplashes	92.9 (1.6)	15.2 (2.3)
	Block3	Highlighted	95.0 (1.0)	54.8 (5.3)

Figures

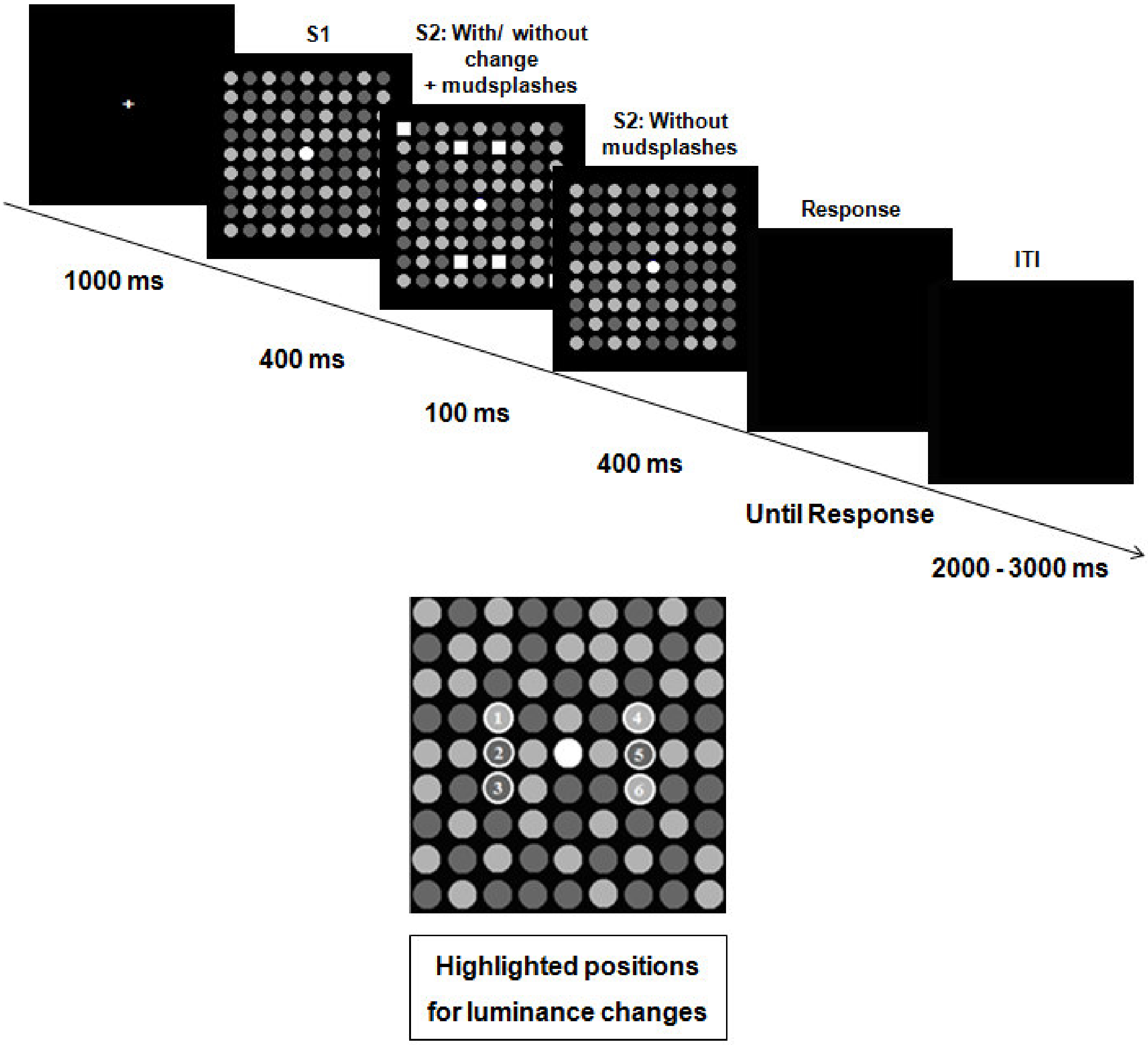

Figure 1. Example of an experimental trial. After a fixation cross (1000 ms), matrix S1 appeared (400 ms), followed by matrix S2 with a possible change (lateral luminance or central color change) (100 ms), simultaneously with the mudsplashes. S2 remained on the screen for another 400 ms without the mudsplashes. Afterward, participants indicated whether they had seen a change or not. Finally an inter-trial interval (ITI) of 2000 – 3000 ms appeared. In this example, six mudsplashes were presented as in Block 1 and 3. In Block 2, four or eight mudsplashes appeared in mixed sequence. The dot in the center of the matrix was colored in either red or green. In the matrix below, the six possible luminance change positions are marked in white color (not visible in the experiment). In Block 3 these positions were permanently marked in red color.

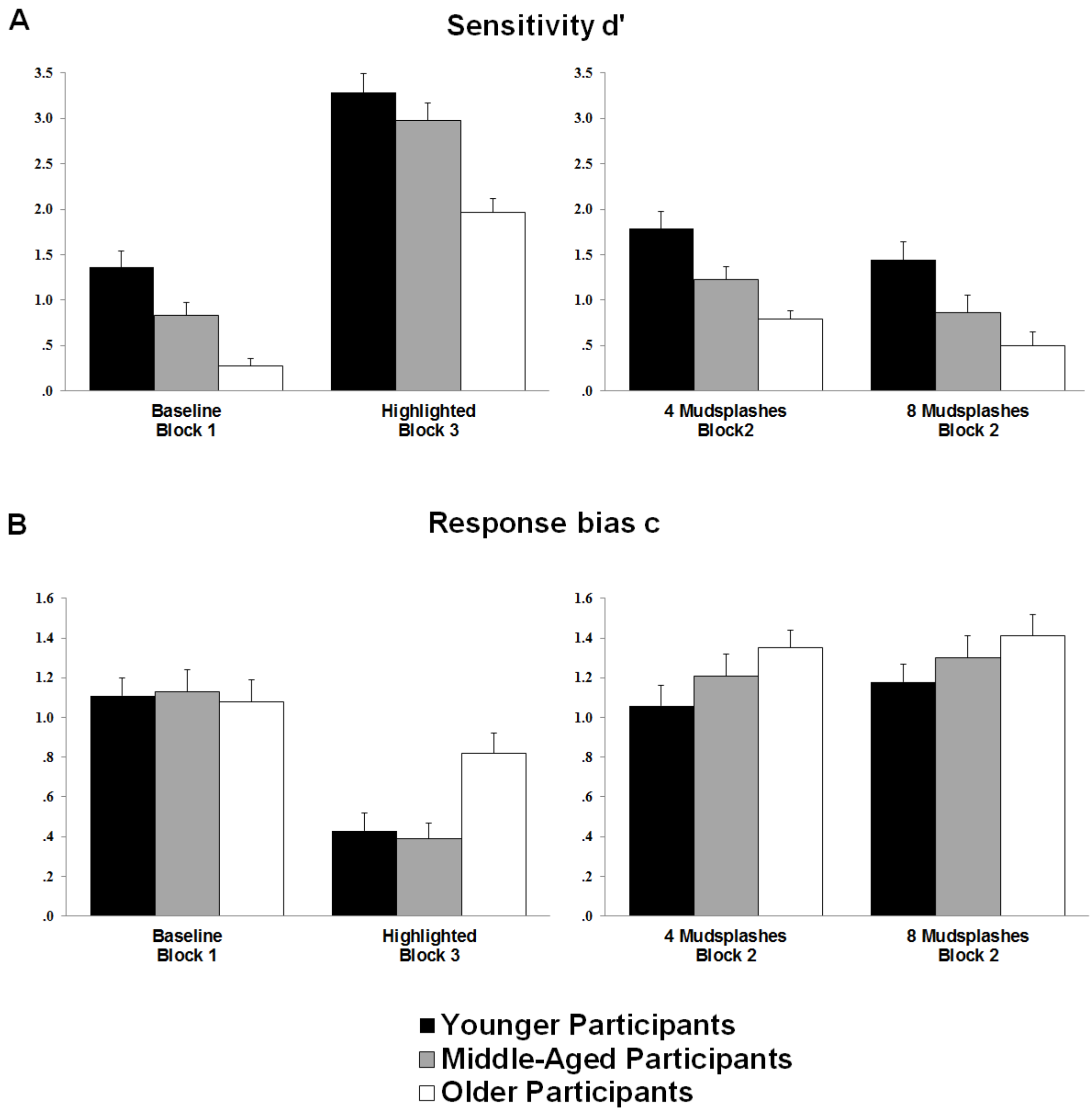

Figure 2. Mean values and standard errors of behavioral data (A = sensitivity *d*'; B = response bias *c*) for all four conditions, separately for younger, middle-aged, and older participants.

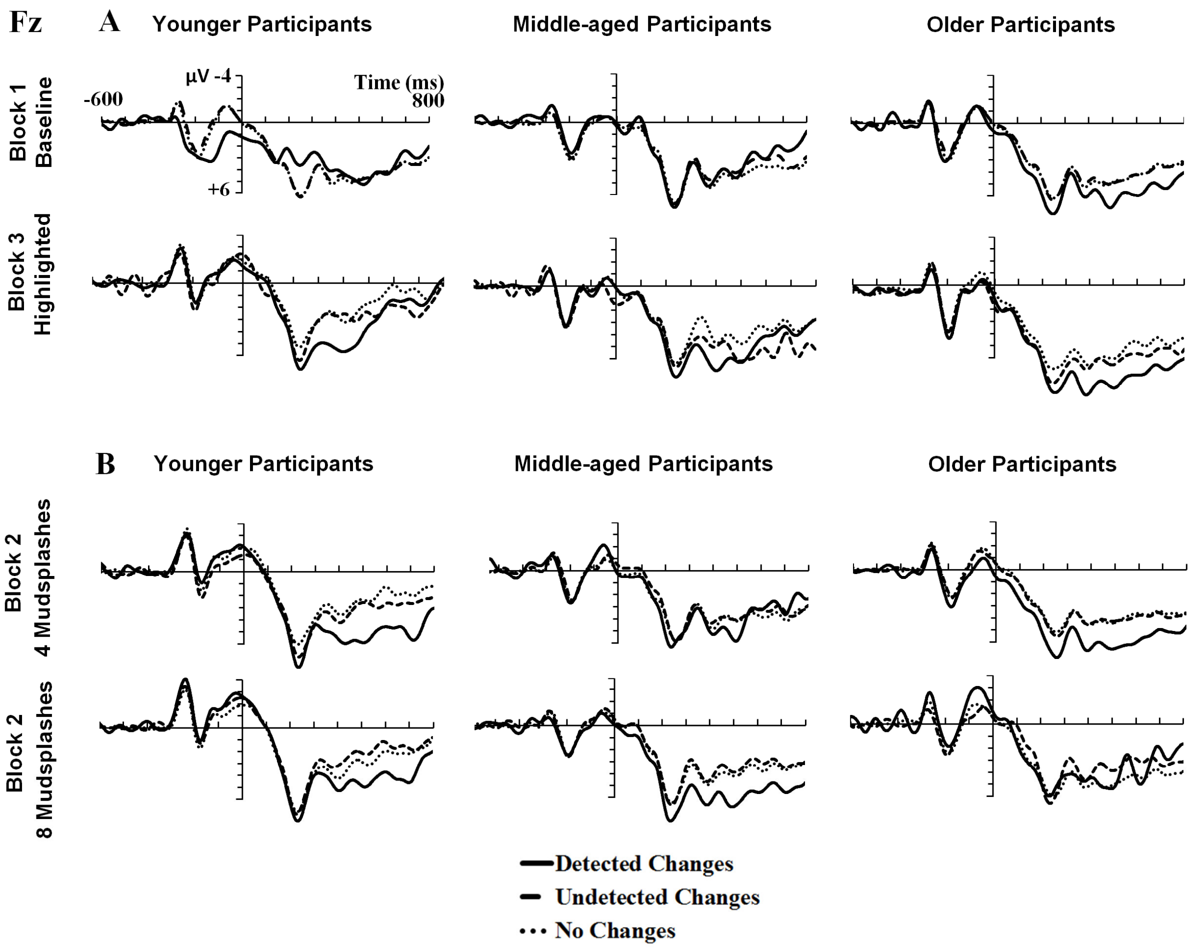

Figure 3. Grand averages of event-related brain potential waveforms as measured at electrode Fz, separately for younger, middle-aged, and older participants and each condition. S2 (change and mudsplashes) was presented at Time 0.

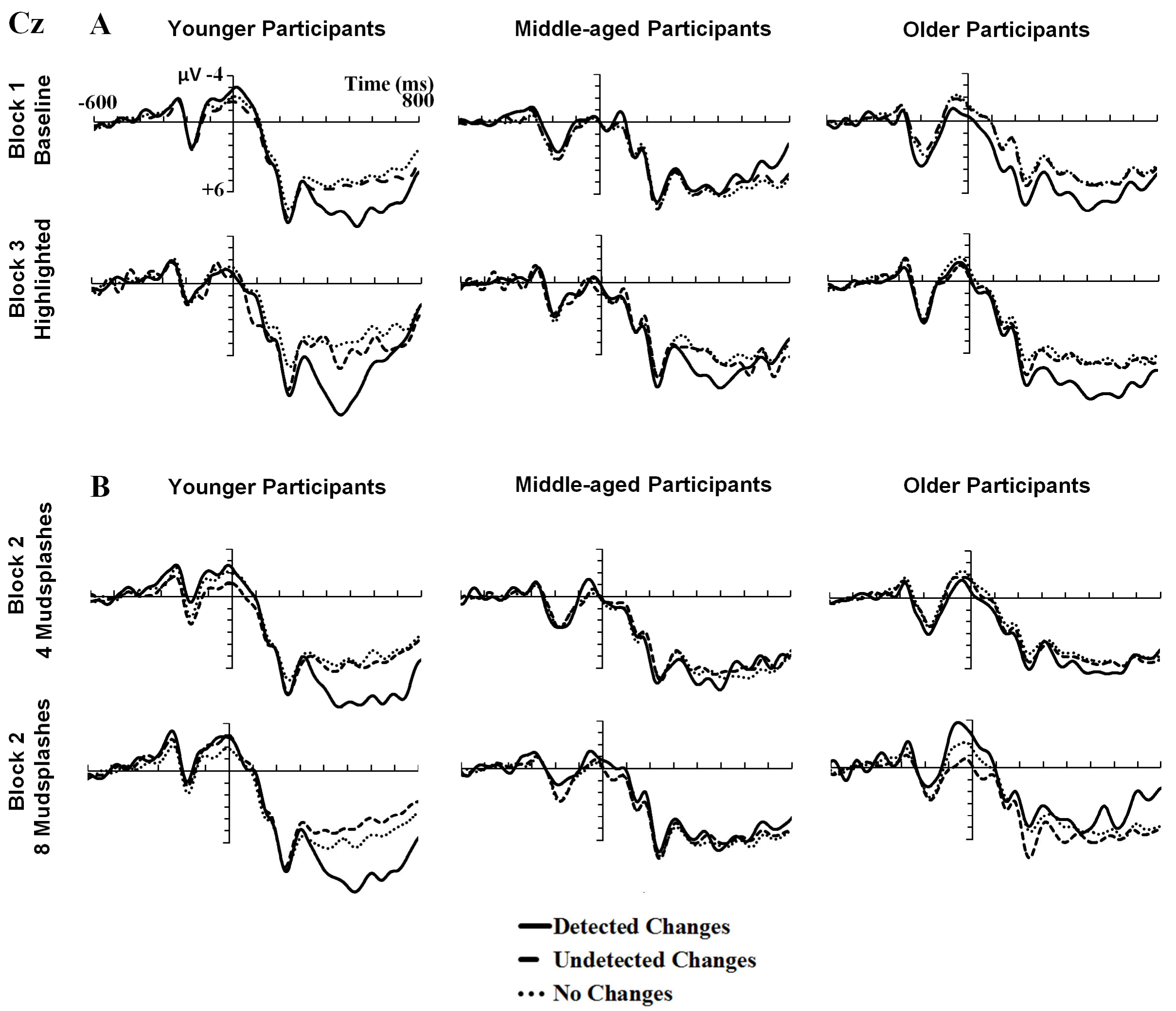

Figure 4. Grand averages of event-related brain potential waveforms as measured at electrode Cz, separately for younger, middle-aged, and older participants and each condition. S2 (change and mudsplashes) was presented at Time 0.

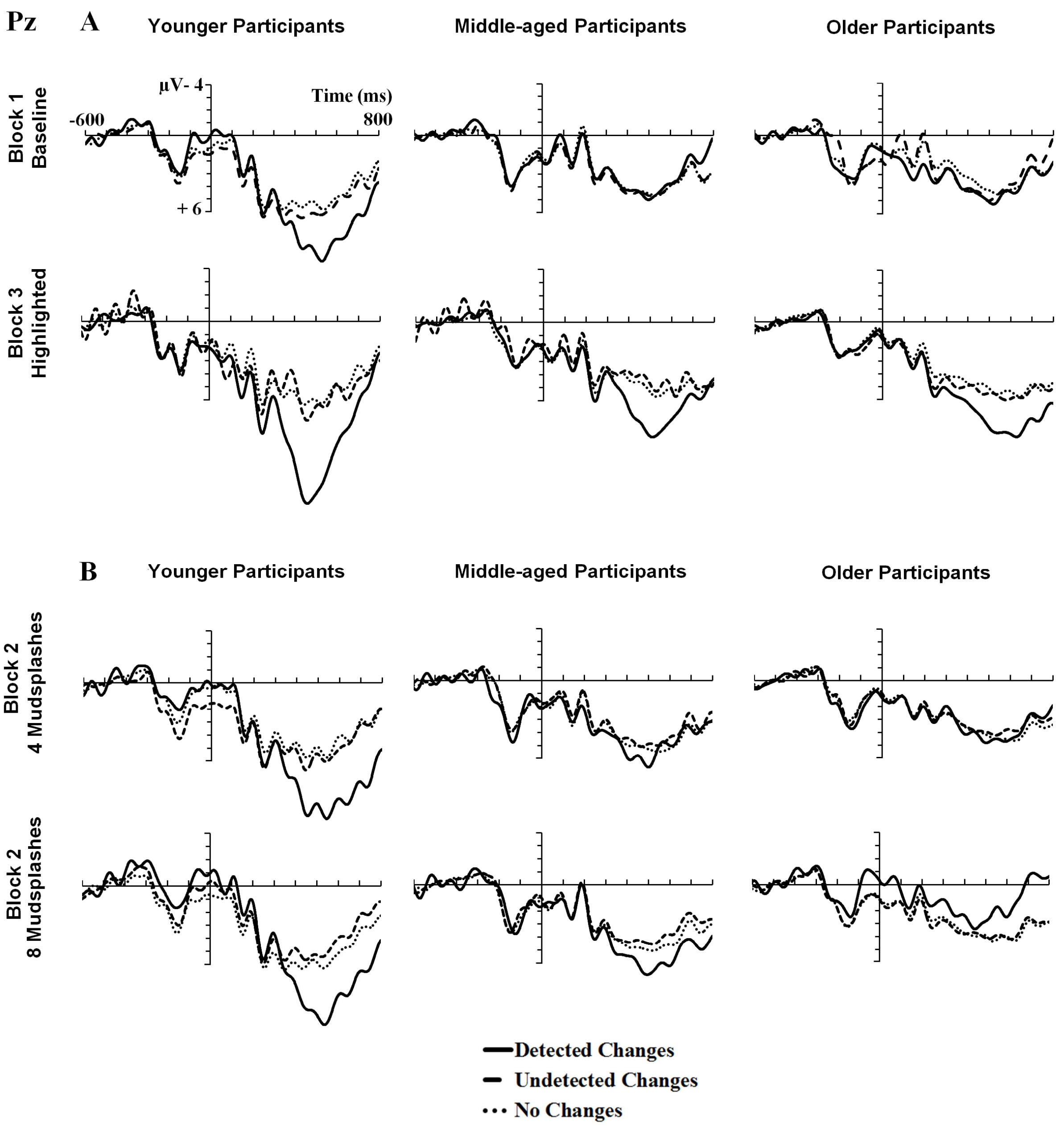

Figure 5. Grand averages of event-related brain potential waveforms as measured at electrode Pz, separately for younger, middle-aged, and older participants and each condition. S2 (change and mudsplashes) was presented at Time 0.

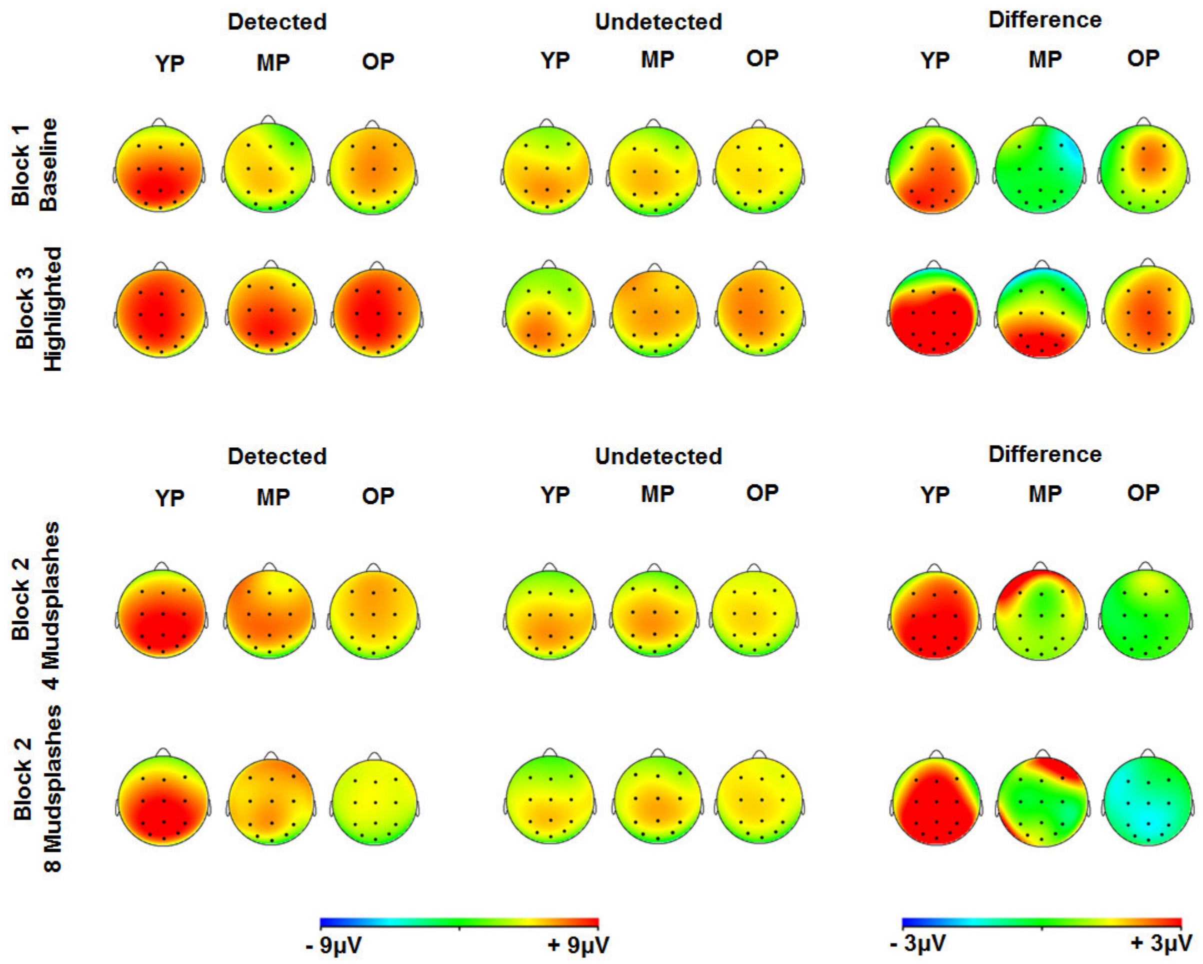

Figure 6. Topographical maps which show the activity in the P3 time window between 400 and 600 ms, separately for each condition and age group (YP = younger participants; MP = middle-aged participants; OP = older participants) for detected and undetected changes as well as their difference waves (detected minus undetected).

Erklärung gemäß § 8 Abs. 1 Buchst. b) und c) der Promotionsordnung der Fakultät für Verhaltens- und Empirische Kulturwissenschaften

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Promotionsausschuss der Fakultät für Verhaltens- und Empirische Kulturwissenschaften der Ruprecht-Karls-Universität Heidelberg

Doctoral Committee of the Faculty of Behavioural and Cultural Studies, of Heidelberg University

Erklärung gemäß § 8 Abs. 1 Buchst. b) der Promotionsordnung der Universität Heidelberg für die Fakultät für Verhaltens- und Empirische Kulturwissenschaften

Declaration in accordance to § 8 (1) b) and § 8 (1) c) of the doctoral degree regulation of Heidelberg University, Faculty of Behavioural and Cultural Studies

Ich erkläre, dass ich die vorgelegte Dissertation selbstständig angefertigt, nur die angegebenen Hilfsmittel benutzt und die Zitate gekennzeichnet habe.

I declare that I have made the submitted dissertation independently, using only the specified tools and have correctly marked all quotations.

Vorname Nachname

First name Family name ____

Datum, Unterschrift

Date, Signature ____