Modeling the role that short term memory stores and attention play in change blindness

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Abstract

Humans tend to think that they see the entire world. However change blindness – the inability to detect salient changes from one view to a next – reveals a different story. Objects in front of people can change without it being noticed. Change blindness does not occur due to poor visibility of the changes, because they can be clearly seen once they are detected. The question addressed in this paper concerns why these salient changes can so easily be missed. The relation between iconic memory, visual short term memory and attention is investigated. How can human access iconic and visual short term memory stores and use this information to detect changes? It is explained why these cognitive functions must operate together in order to detect changes. A new model is presented that describes the role that attention, iconic memory and Visual Short-Term Memory (VSTM) play. In order to detect changes attended stimuli from iconic memory or a fragile part of VSTM are transferred to a robust form of VSTM. This is necessary for change detection, because representations in the robust part of VSTM are solid enough to detect changes before they are lost from memory.

Keywords

Change blindness, attention, iconic memory and visual short term memory

Introduction

When people see a scene, they are convinced that they have a conscious representation of the entire scene. In contrast to what these persons think, research shows that they are not always aware of everything they see (Rensink, 2000). This is clearly observed in change blindness paradigms. Change blindness can be seen as an inability to detect a change from one view of a scene to a next view in which the scene has been changed (Simons and Levin, 1997). When these changes are known there is no deficit to detect changes, and people find it quite striking that they missed the change. Hence, change blindness is not the result of stimulus properties, like low contrast, or crowding etc.

Changes are not always missed. There are factors that facilitate change detection. In this thesis some factors that play a role in the nature of change detection will be presented by reviewing the literature. The goal of this paper is to show that memory and attention play a key role in change blindness. If memory and attention are so important in change blindness, then change blindness might be a useful paradigm to study the relation between memory and attention.

Change blindness

There are different ways of testing change blindness. What these experimental procedures usually have in common is that they observe how well changes are detected. Thus in order to tell about change blindness we will elaborate on what detections and changes are.

Change detection in the current article can be seen as the visual event where a change is noticed. A detected change can be classified in multiple levels: the lowest is the detection of change without being aware of what object changed and where this occurred. The second level is the ability to identify the object that changes and thirdly the ability to report the precise location of a change (Rensink, 2002). Thus a detection of a change can be the notion of a change, even better is: knowing where the change occurred and knowing which object changed.

The former paragraph described what a detection was, but what is a change exactly? The definition of Rensink (2002) is adopted: “The word *change* generally refers to a transformation or modification of something over time. As such, this notion presumes a nonchanging substrate on which changes are imposed. More precisely, change is defined here as the transformation over time of a well-defined, enduring structure. The complexity of the structure does not matter – it can range from an undifferentiated particle to a highly articulated object.” Sometimes it is unclear what the distinction between motion and change is. A change is not motion. For example: the motion in a moving dot patch can be seen as a property of the dot patch. The speed and direction of the motion can be as easily measured as the color or luminance of an object that can be suspect to change. In this sense a change is more than motion, since motion can be the property that changes. Another distinction that should be made is the difference between a change and a difference. Difference is different from change because it describes the properties of objects that are dissimilar, but of simultaneously presented objects and not the same object. In contrast to difference, change refers to a transformation within a single object that is altered over subsequent presentations or time. For more a more detailed description of change see Rensink (2002).

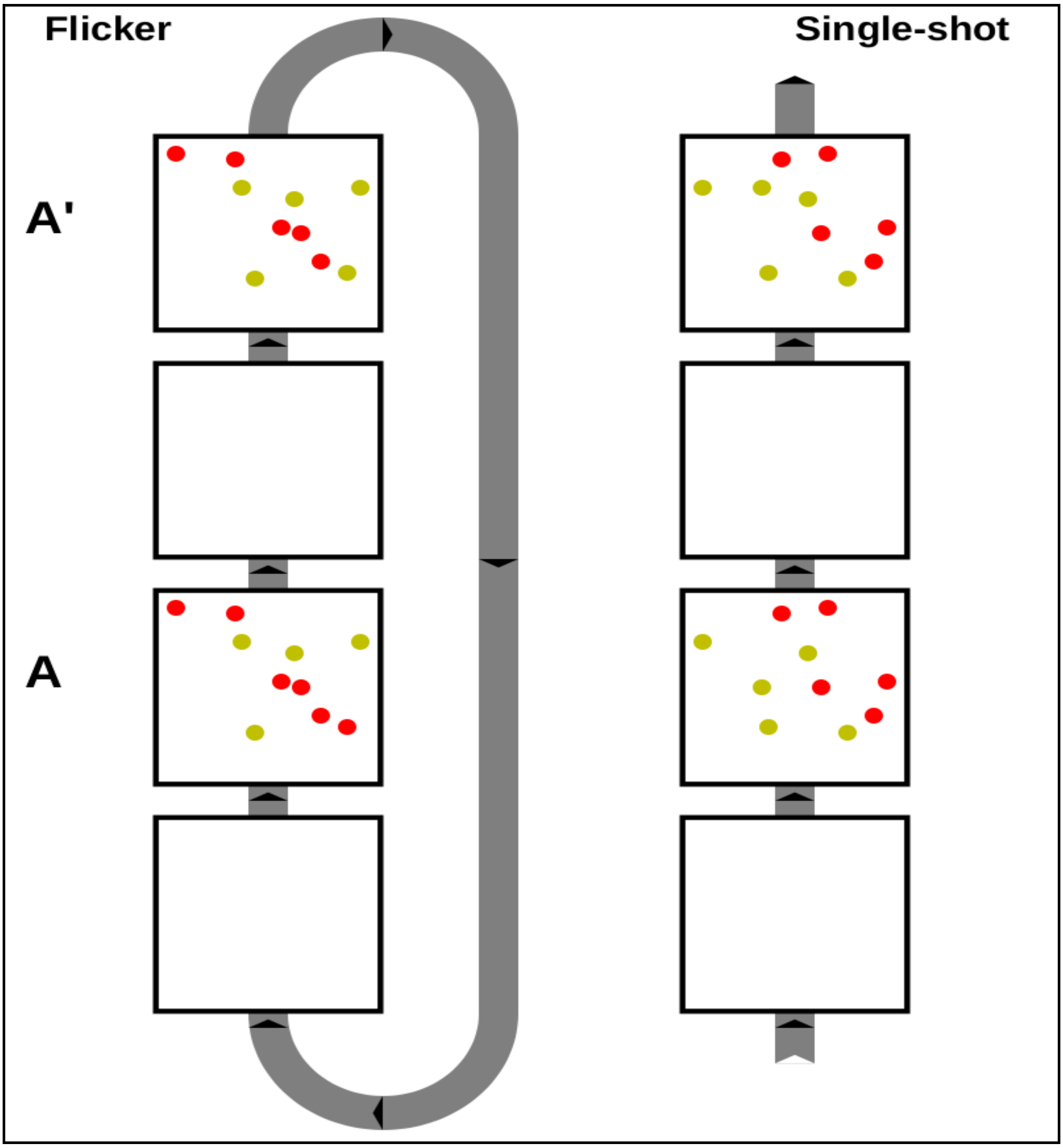

Figure 1. The flicker and single-shot paradigms. In both types of paradigms is an original picture of objects (A) and a change picture. The original is indicated in the figure as A and the changed one is called A’. A’ has one modification compared to A. Between picture A and A’ a blank screen is presented and in case of the flicker paradigm also between A’ and A. The flicker paradigm keeps looping until the change has been found by the participant. Therefore the most suitable dependent measure is reaction time. In the single-shot paradigm reaction time can be used, however usually accuracy is the main response variable. The single shot paradigm can be used as a two alternative forced choice paradigm where a participant judges whether both pictures are the same, or whether there was a change. In the flicker paradigm an example is shown where one of the dots changes color, whereas in the single shot experiment one of the object undergoes a location alteration. These examples show abstract stimuli, but these paradigms work well with pictures of real life situations.

There are multiple ways to demonstrate change blindness in different experimental paradigms. These experimental procedures have been conducted using artificial low level visual stimuli, but also with real life examples showing the ecological validity of this phenomenon. The two main experimental paradigms are the single shot and the flicker paradigm (see Figure 1). The single shot paradigm has one change (e.g. Blackmore, Brelstaff, Nelson & Troscianko, 1995; Levin & Simons 1997). Between two successive pictures another picture is presented which is usually blank. After the second/changed picture is shown, the participant has to indicate what changed and usually accuracy is the main dependent measure. In the flicker paradigm two scenes are alternating with an empty screen in between (e.g. Rensink 1997). In this paradigm it is more suitable to measure Reaction Times (RTs).

A central question in change blindness is: when does it occur? Most of the research shows there is a pre view and a post view of a scene and something is intervening between the two views. Therefore it is interesting to examine the scenes and what could be intervening between the two views to examine why change blindness occurs.

Pashler (1988) examined multiple factors that could result in change blindness, the first factor was: does prolonging the stimulus *presentation duration* of a pre-change picture increase change detection? The second factor was *masking*; can intervening masks between two pictures enhance change blindness? This can be a factor in change blindness since it can mask the pre-change stimulus. The third factor was *Inter Stimulus Interval* (ISI), is change blindness stronger when the time between a first and second array is increased? This can play a role since the first image might be subject to decay. Finally, does *familiarity* with the stimuli enhance change detection? To test the influence of stimulus duration Pashler (1988) showed participants two arrays of letters in a single shot paradigm. The second array was the same, or one letter was changed. ISIs longer than 60 ms significantly impaired change detection. However, prolonging the stimulus duration of the pre-change array did enhance change detection, but only mildly. Hence, the first experiment of this study showed that prolonged stimulus presentation duration with a similar ISI results in facilitated change detection. In his second experiment the ISI was manipulated (34, 67 & 217 ms) with a fixed duration of the stimulus. The second factor addressed in the second experiment was masking. On some of the trials the first stimulus array was masked. The results show that especially during the shortest ISI trials masking interfered with change detection, on masked trials the d’ from signal detection theory (sensitivity) and the number of correct change detections was low. Additionally, there was an overall effect of ISI where d’ and target detection was good on the trials with short ISI. In the third experiment from this study the role of stimulus familiarity was examined. On all different lengths of the ISI it did not matter whether there was a familiar character or a character that was turned upside down (the unfamiliar character). There was only an influence of ISI; with 34 ms ISIs it was clear that the performance was good, which counted for both the familiar and the unfamiliar characters. The authors controlled whether this might be due to the possibility that a participant could rotate the reflected letters to their normal orientation. Therefore in experiment 4 Pashler (1988) added a shorter stimulus duration condition to rule out that the letters were rotated. However, this did not seem to matter. Therefore Pashler (1988) concludes that: one, prolonging stimulus duration can enhance change detection. Two, ISIs shorter than 67 ms enhance change detection. However, masking the initial stimulus array impairs this enhancement. Finally, Stimulus familiarity is not an issue in change detection; it does not facilitate change detection.

Saccades create a transient all over the retinas, because every pattern of light is displaced equally to the size of the eye movement. Such a global transient easily masks the transient of a local object change. Another reason that such a local change is not detected can be due to the fact that the visual system is “blind” during the trajectory of a saccade. The temporary blindness is called saccadic suppression (e.g. Matin, 1974). Therefore it is conceivable that a saccade could intervene between different views of a scene and induce change blindness when the scene is transformed during the saccade. McConkie and Currie (1996) showed pictures of complex scenes of e.g. a picture with a house, a tree and a driveway. They shifted the pictures a little higher, lower etc. when participants made a saccade over the scene. They noticed that how larger the saccade and how smaller the shift of the picture was, the less likely the participants were able to detect the shift of the picture. This showed that change blindness can be induced while a saccade is launched, and how larger the saccade the less likely that changes were detected. A second experiment manipulated the size of the objects. This examination provided the result that size changes also go unnoticed as saccade length increases. Grimes (1996) conducted a similar experiment, however here the changes occurred within the scene participants saw, not the entire picture as in McConkie and Currie (1996). Grimes (1996) also argued that changes are missed if they occur during the trajectory of a saccade. One of the reasons alterations in the pictures are missed, is that the visual system is suppressed during a saccade. Thus someone can see the change only before or after a saccade and therefore change blindness is likely when stimuli change during saccades.

To examine change blindness in stable viewing conditions, Rensink, O’Regan and Clark (1997) examined change blindness in absence of the influences of saccades. As was indicated in the previous paragraph, a saccade can be seen as a visual transient over the entire visual field. Another way to create such a transient is to replace a picture by a blank/white screen. In contrast to saccades, blank screens can be controlled by the experimenter. Therefore, Rensink et al. (1997) developed a flicker paradigm (see, Figure 1). Rensink et al (1997) showed pictures of real life situations. In this paradigm participants saw picture *A* and modified picture *A'* alternating. Brief blank screens were in between an alteration. Some of the changes were in objects of marginal interest and others were in objects of central interest. The distinction between objects of central and marginal interest was made in a different experiment; observers rated how interesting an object was. Thus, Rensink et al. (1997) also tried to find whether changes were more easily detected when an object was naturally more interesting. The effects of the degree of interest were striking. It took many more alterations before changes in objects with a low degree of interest were detected. The authors also showed that the difficulty to detect changes was not related to the duration of the stimulus. They showed that a cue word before the trial, facilitated change detection. That showed that if participants know where to look they will find the change much easier. From this data Rensink et al. (1997) concluded: in order to perceive a change an object must be given sufficient attention. In the absence of attention the contents of visual memory will be overwritten. When participants know where to look they will not have problems to detect changes.

Other examples of change blindness are: the inability to note changes that occur between different camera angles or cuts (Levin & Simons, 1997), during eye blinks (O'Regan, Deubel, Clark & Rensink, 2000), in real-life situation (Simons & Levin, 1998) or during picture movement (Blackmore, Brelstaff, Nelson & Troscianko, 1995). All these change blindness paradigms that have been summarized so far, contained a brief period of visual disruption. Therefore, one possibility is that this visual disruption overwrites the pre change image and the subsequent post change scene can therefore not be compared with the original image.

However, recently some other striking features of change blindness have been found in absence of visual disruption like a blank screen, saccade etc. Under stable viewing conditions participants of Simons, Franconeri and Reimer (2000) saw addition or deletion of objects gradually over 12 seconds, thus there was no immediate change or visual disruption. Although the changes were perfectly visible if they happened instantaneously, the gradual change did not capture attention to the change. Therefore these slow changes were missed. This shows that visual disruption is not necessary for change blindness to occur. Simons et al.

(2000) argued that this form of change blindness occurred due to an absence of an acute event that draws attention to the alteration. Simons et al. (2000) and Rensink et al. (1997) already showed that attention is a critical factor in change blindness, therefore it is useful to discuss what role attention actually plays.

Coherence Theory

The previous experiments showed that attention helps overcoming change blindness. These data led towards the development of *Coherence Theory* (Rensink, 2000). In this theory stimuli falling on our retinas form proto-objects, which can be quite complex but have a very short existence. Consequently, the proto-objects are replaced by new stimuli falling on the same retinal location. Then, in order to detect changes, focused attention should grasp proto-objects before they are replaced by new stimuli and keep them coherent or stable over time. After the coherent object has been used for change detection it will be passed back to its proto-object form. Thus unattended objects are volatile and subject to overwriting, whereas objects that are attended become coherent over space and time, and are therefore useable for change detection.

A model of change blindness and the factors that play a role

We suggest a model that is partly similar to Rensinks coherence theory (2000). Our model (Figure 2) illustrates four important characteristics of change blindness. First, it tries to answer the question how attention facilitates change detection. Secondly, we model the role that short term memory stores play in change detection. Thirdly, we model how short term memory and attention must operate together in order to overcome change blindness. Finally, the model that we present illustrates the neurophysiological basis of change detection. The first characteristic is similar to coherence theory. However, the remaining three points are not explained in coherence theory and make our model new and more elaborate. Additionally, our model describes how people can overcome change blindness in well defined psychological constructs, like iconic memory (Sperling, 1960), VSTM (Cowan, 2001) and attention. As we will see, classical psychological constructs are not sufficient to explain change blindness and therefore a recently discovered type of VSTM will be presented. We will present one new type of memory that resembles a memory stage between iconic memory (Sperling, 1960) and Visual Short Term Memory (VSTM) (Cowan, 2001). Before we can present our model we should first discuss attention, iconic and visual short term memory, because they are the pillars of our model.

Attention

In our model there is a prominent place for the role that attention plays. Here follows a brief review of attention. Everyone seems to know what attention is, however it is more complicated than most people think. The world surrounds human with more information than they are able to cope with. To solve this problem the first property of attention is selection, for a review see Treisman (1969). Selective attention allows humans to deal with the information that is necessary for current purposes. All information is filtered by a mechanism that allows the attended information to pass (Broadbent, 1958). Attention is often demonstrated by ambiguous stimuli, which are stimuli that can be perceived in more than one way e.g. the Necker cube. Attention can focus on one of the percepts in favor of the other. This type of selective attention can be seen as a top-down influence of the attentional mechanisms. In contrast if the attentional filtering mechanism is influenced not by a person self, but by stimuli in the environment, attention might be drawn towards salient events. For example a singleton e.g. a red colored object between white distracter stimuli draws attention involuntarily (Theeuwes, 1992; Connor, Egeth & Yantis 2004). On the other hand, attention can be directed to spatial locations (Brefczynski & DeYoe 1999) or to features like motion, or the tilt in comparison to a vertical orientation (Kanai, Tsuchiya & Verstraten, 2006). Attention is tightly coupled with awareness/consciousness, however it is most likely not the same (Lamme, 2003; Koch & Tsuchiya, 2007). Attention can be beneficial for or modulate perception of stimuli that would not be seen otherwise (Pestilli & Carrasco, 2005). The fact that attention modulates what people perceive does not only change their behavior, but it also affects neuronal processing in the visual brain (Luck & Ford, 1998; Tootell, Hadjikhani, Hall, Marrett, Vanduffel, Vaughan & Dale, 1998).

Thus, attention is a mechanism that filters the vast amount of stimuli that reach our senses in order to process the most important stimuli; attention is selective. Top-down influences can direct attention to spatial locations or features; attention can be controlled. Salient events in our environment are able to capture attention involuntary, by means of bottom-up stimulus properties. Stimuli in the locus of attention are processed more efficiently. Although attention is closely related to consciousness, these are two different psychological constructs.

Iconic and visual short-term memory

Above quite some data have been presented that illustrate that change blindness can be striking. People overlook changes that should be clearly visible. One of the reasons that people miss quite salient changes in their environment is their limited capability to access all information that falls on the retina. In the sixties of the previous century, a remarkable short term visual buffer was found by Sperling (1960). An often used term for this visual buffer is *iconic memory*. Sperling (1960) presented arrays of letters. The letters were presented in three rows with four columns. If participants were asked to make a report of all letters – the full report – they had great trouble to recall all letters. However, if participants were cued to report one row of four letters – the partial report – they were almost always able to recall all four letters correctly. It must be noted that the cue was presented after the offset of the stimulus array, but this only worked if they were cued within approximately 250ms after the offset. This shows that iconic memory stores a vast amount of information for a very short duration.

Another form of memory is Visual Short-Term Memory (VSTM). This is also a relatively short term store. The lifetime of VSTM is longer than iconic memory. However, the more durable VSTM comes at the cost of the amount of information that can be stored. The information stored in visual sensory memory is approaching infinity, whereas the maximum in VSTM is about four objects (Cowan, 2001). Luck and Vogel (1997) showed that four objects with multiple features could be retained in VSTM just as easily as four single feature objects. This indicated that the number of features which are retained in memory can exceed four if they are integrated, whereas it is not possible to retain more than four single feature objects in VSTM. Thus, objects in VSTM are fully integrated instead of a number of separate features (Luck and Vogel, 1997). The number of storable objects can be a little smaller than four items if the objects have a rich list of features that are subject to change (Alvarez & Cavanagh, 2000). When the time between the sample and test array is short e.g. < 1 second, iconic memory can facilitate the capacity beyond four items (Philips, 1974). In summary, iconic/sensory memory is very short lasting but has a (near) infinite capacity; VSTM last longer but the number of objects is reduced to four and here the objects are integrated.

The model

Now that attention, iconic and visual short term memory have been discussed we can turn to our model (Figure 2). The goal of the model is to explain which conditions have to be met to make someone capable of detecting changes. This goal should be achieved by elaborating on the roles that attention, iconic memory and VSTM play. Subsequently, the model will show the neurophysiology that mediates these cognitive processes. After the model is explained we present the data that underlies the model and shows its validity.

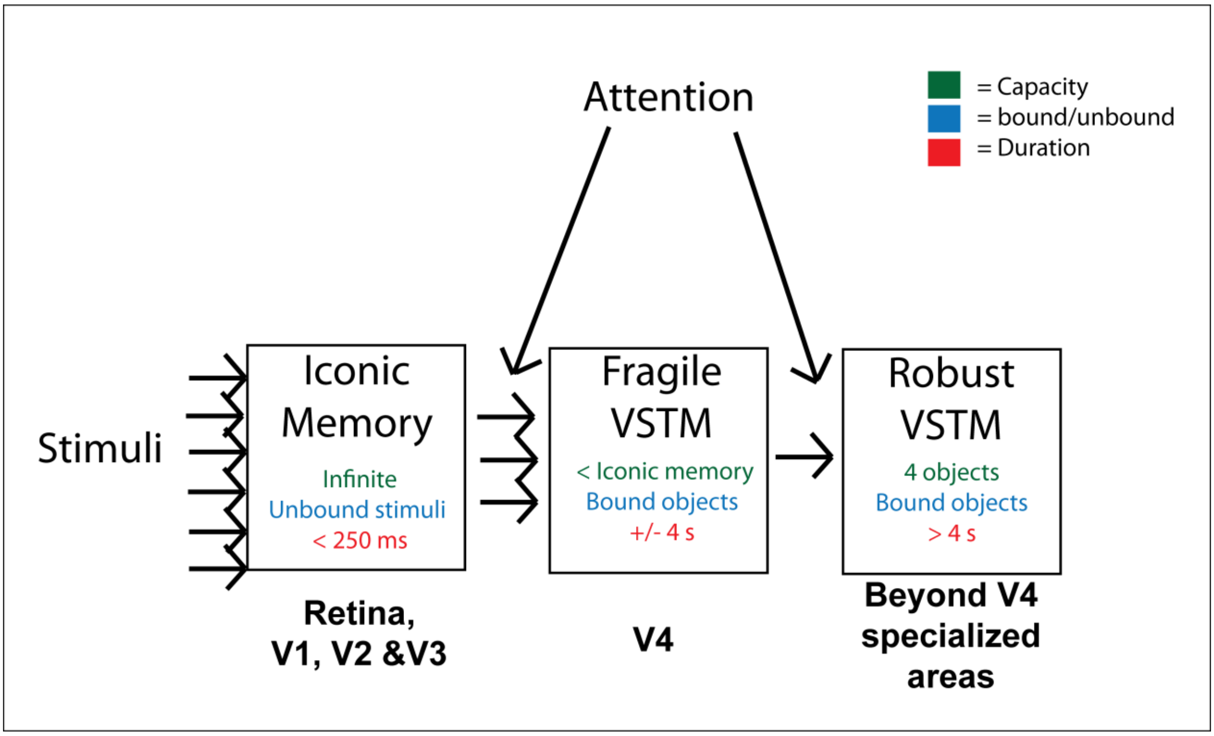

Figure 2. An overview of what we have learned from the phenomenon of change blindness. Stimuli fall on our retinas, and are passed to iconic memory, which is a detailed, but an unbound representation of what we see. The stimuli can travel via fragile VSTM to robust VSTM. However, if there are many objects that are subject to possible change, then it is unlikely that the object that changes arrives in robust VSTM. The capacity of fragile VSTM is rather large so it is still likely that a representation of a changing object arrives here. However, it is unlikely that the stimulus is transferred to robust VSTM, since that only has room for maximally four items. Therefore attention needs to be fast and read the information from iconic memory or fragile VSTM respectively. Attention will transfer the attended object to robust VSTM as a kind of insurance that a change will be detected. Iconic memory relies on very early visual processing like in the retina or V1, V2 and V3. The fragile part of VSTM is dependent on V4 and robust VSTM relies on areas beyond V4, where processing of stimuli is very stimulus specific, like the fusiform gyrus for faces, MT for motion and the hippocampal place area for places.

To start explaining the model (Figure 2) we begin with the memory system where information about our visual world must be stored in order to detect changes. An object that is subject to change must be stored inside the robust part of VSTM (Figure 2). If a stimulus is represented in robust VSTM it will survive for a relatively long time; this enables comparison with a subsequent view of the same scene to see if the object is changed. This makes the robust part of VSTM different from fragile VSTM and iconic memory in the model. As indicated in Figure 2 there is only room for four integrated objects with all their features. This makes it possible to cognitively monitor whether one of the features of the object has changed over time. Thus this leads to the question which conditions must be met for a stimulus to arrive in the robust part of VSTM, because if it arrives in robust VSTM the conditions for change detection are met.

Since we currently know that a stimulus must arrive in robust VSTM for change detection, we can explain how a stimulus can arrive in the robust part of VSTM. As indicated in Figure 2, there can be many stimuli that fall on our retinas. When they fall on our retinas, they are passed on to iconic memory. Virtually every stimulus that reaches our eyes is represented in iconic memory, for the capacity is unlimited (Spearling, 1960). Then, quite some stimuli from iconic memory are transferred to the fragile part of VSTM. This fragile part of VSTM is a very recently discovered type of memory (Landman, Spekreijse & Lamme, 2003; Sligte, Scholte & Lamme, 2008; Sligte, Scholte & Lamme, 2009). Fragile VSTM will be discussed in more detail later, but for now we will define it as a form of short term memory that is intermediate to iconic and robust VSTM. It is between those two memory structures, since it has a lower capacity than iconic memory but is more stable over time, but it is larger than and not so robust over time as robust VSTM. Finally, four objects from fragile VSTM are transferred to robust VSTM. However, the important question is, is the object that changes one of those four objects that are passed to robust VSTM? If the object is not one of the four that is transferred to robust VSTM changes will not be detected.

Fortunately humans have a mechanism that has control over which objects are transferred to robust VSTM. That mechanism is attention. Our model proposes that if an object is attended to, then it will be passed on towards the robust part of VSTM. Therefore if an object is attended to, and the attended object is the object that changes, the change will be detected. However, since stimuli in iconic memory and fragile VSTM are not stable over time we must discuss the role that time plays. If items are to be transferred from iconic memory to robust VSTM, an attentional cue should arrive within 250 ms, for otherwise the iconic image is lost. If a cue arrives between 1 and 4 seconds after the presentation of stimuli, we are able to retrieve objects from fragile VSTM. As we will show later, objects or features are lost from iconic memory through overwriting of the pre-change stimuli; an object that changes overwrites the pre-change representation.

So far, we have discussed the following points about the cognition of change blindness. Firstly, objects should be in the robust part of VSTM to be able to detect changes. Secondly, some objects will be passed from fragile VSTM or iconic memory to robust VSTM. Thirdly, attended stimuli are definitely transferred to robust VSTM, hence if attended stimuli are changed, the change will be detected. Finally, unattended stimuli are overwritten by subsequently presented stimuli, which can mask changes.

Now that the cognitive structures in or model have been discussed, the neural basis of the model is presented. To start with iconic memory, it is represented very early in the visual stream and most likely dependent on aftereffects in the retina, V1, V2 and V3. Fragile VSTM seems to be dependent on V4 (Sligte et al., 2009). Finally, to be able to detect changes in objects, they must be stored in robust VSTM. The neurons here must be very stimulus specific, like visual area V5 (MT) for motion or the fusiform face area for faces. These neurons must be so specific because they need to be able to detect whether stimuli are changed over time.

The role of attention in change blindness

Attention and perception have an influence on each other; objects in the locus of attention are better perceived. For example attention can enhance contrast sensitivity to attended stimuli (Pestilli & Carrasco, 2005). On the other hand Pestilli and Carrasco (2005) also showed that cueing attention invalidly impairs contrast sensitivity. One last example of how attention modifies what humans see is *inattentional blindness*. When participants are instructed to observe how often a team throws a ball they completely miss a monkey, or a woman with umbrella walking through the playfield (see e.g. Simons & Chabris, 1999). Thus attending to the ball makes otherwise normally salient events completely overlooked. Thus there is a relation between attention and perception which can possibly affect change detection. Now we can turn to the question how attention affects change blindness.

A key player that helps to overcome change blindness could be attention. As was demonstrated with inattentional blindness salient features can be overlooked. Hence, it is not inconceivable that items that draw attention away from changing objects impair change detection. O’Regan, Rensink and Clark (1999) showed that sudden ‘mudsplashes’ (rectangles with a black and white texture) disrupt the visual representation of a scene. This is due to the mudsplashes being visual transients themselves. This causes an impairment of detecting changes of objects, object size and location, even while the change location was not occluded by the splashes (O’Regan et al., 1999). Change blindness occurred mainly during trials where the change was in a region of marginal interest, if the change was in central interest than it was immediately apparent. This showed that even though the splashes did not occlude the objects that changed, a percept of an image is severely degraded. The interpretation of these results points in the direction that a visual disruption (a blank screen in the flicker or single shot paradigm) on the location of the change is not really necessary. The reason that change blindness was induced is due to that mudsplashes are visual transients themselves. They capture attention by means of bottom-up stimulus properties, and thereby reduce the amount attention that is left to look for changes. This indicates for our model that if attention captured by these mudsplashes, relevant transients from the changes are not being used and therefore mudsplashes induce change blindness.

Drawing attention away from changes is not the only way to test whether attention is related to change detection. Some people have more attention available than others. Thus if attention is related to change blindness, then people with a large amount of attention should find changes relatively well. Pringle, Irwin, Kramer & Atchley (2001) saw the Functional Field Of View (FFOV) as the spatial area where a task can be performed successfully and the authors assumed that a as task becomes more difficult that the FFOV becomes smaller. The authors saw the FFOV as a measure for the quantity of attention that a participant can allocate. Thus they argued that if the attentional breadth is large, so is the possibility to detect changes in a flicker paradigm. Pringle et al (2001) also looked at four other factors: eccentricity of the change, salience, age of the participant and meaningfulness. Salient changes, changes of meaningful objects, changes in the origin of a picture and low age facilitated change detection. Concluding, Pringle et al (2001) showed that attentional breadth was negatively correlated with the latency of change detection. Thus a large FFOV coincides with successful change detection showing that how more attention is available to someone the easier it is to detect changes. As our model predicts if participants have a lot of attention available, it is very likely that changes are captured resulting in attenuated change blindness.

Modulation of attention facilitates change detection

The last section showed that attention is related to change blindness. Therefore it is conceivable that a change in object, size, etc. on the location where someone is attending, is easier detected than changes outside of attention. However in the previous section attention was endogenously captured; if the changing item was of interest of the participant, then change detection is facilitated. Thus another question is, is it possible to draw attention to the place where the change is about to occur, by methods more related to bottom-up attentional mechanisms?

Rensink et al. (1997), as discussed earlier, had already shown that objects in the center of interest were prone to rapid change detection. However, the way of determining the level of interest, was not really well controlled. The objects that were marginally interesting versus objects that were in the center of interest were determined by human raters. This is not a very reliable method to guide attention towards objects in the center of interest. What might have been appealing to the persons determining the interest of the objects in the pictures was not of interest for the participants. It could also be that objects in the center of interest are not in the locus of attention. One could say that attention in the study of Rensink et al. (1997) was *endogenous*; the participants themselves were in control of how appealing an object was. In contrast, attention can also be drawn *exogenously*. This can be achieved by delayed onset of the attention capturing item, because sudden onsets capture attention (E.g. Yantis & Jonides, 1990). Another way is presenting the item in a different color - a color singleton - (e.g. Todd & Kramer, 1994). Therefore, a new study was conducted to examine the role of attention in a better controlled fashion (Scholl, 2000). Attention was captured exogenously to one item in an array of 12 objects. The paradigm used in this study was based on the flicker paradigm. The two conditions where attention was captured contained control trials, in the control trials were no or invalid color singletons and none of the objects or an invalid item had a delayed onset. Although the singleton or delayed item was completely unrelated to the changing item, change blindness was attenuated when the changing object was the attention capturing item. This occurred even though the participants were fully aware that the attention capturing item was just as likely to change as any other item. This study showed in a controlled fashion that attention to the changing visual field helps overcoming change blindness. This study therefore confirms that attention can be drawn exogenously, or via bottom-up mechanisms in order to overcome change blindness.

There are many ways to capture attention to a specific region in visual scenes. Cavanaugh and Wurtz (2004) found an intriguing way to have monkeys (macaca mulatta) shift their attention. First they examined whether change blindness occurs in monkeys as it does in humans. A task was developed which contained a fixation cross in the middle of a screen and three moving dot patches. The change was a different direction of movement of one of the three patches. Like humans, monkeys responded faster and more accurate when there was a valid cue (dot on patch location) to a patch. Most importantly, they did the same experiment without visual cues. Attention was directed by stimulating the superior colliculus. This stimulation improved attention to a corresponding spatial location on the screen. If midbrain stimulation coincided with the changing movement direction of the patches, change detection was highly improved. This showed that if spatial attention is directed to a location of a change, the probability that the change is overlooked is lower. Thus this indicates that if attention is directed to a spatial location of a change, then the stimulus on that location is shifted to a durable store that allows for the detection of changes.

Change Blindness, attention and capacity in iconic and visual short term memory

Our model we includes three cognitive memory stores: iconic memory (e.g. Sperling 1960) and a fragile and a robust form of VSTM. In the following paragraphs we will explain how VSTM and iconic memory play a role in change blindness. Traditionally VSTM has been considered as one unitary cognitive function (e.g. Cowan, 2001). However, in the end of the next section we will show change blindness experiments that provided data indicating that there is another type of memory store besides iconic memory and the traditional form of VSTM.

Attention is important because it allows for reading of short term stores

Now imagine that something changes within the visual world, but the change gets masked, or our visual representation gets distorted by mudsplashes, saccades etc. What change blindness then shows, is that when our view is unstable we will not be able to compare the view that we had with the image we are currently viewing. Although change blindness suggests that people cannot represent a great deal of the daily world, iconic memory does. In order to examine whether relevant information could be temporarily stored in a short term buffer, Becker, Anstis and Pashler (2000) examined the role of iconic memory in change blindness. They argued that it could easily be the case that there is more represented of an array of objects than change blindness might suggest. To test this hypothesis a cue to the changing item was presented. If this cue was quick enough to retrieve relevant objects from iconic memory a large type of memory before change blindness could be illustrated. In the experiment of Becker et al. (2000) they showed two arrays of letters. Between the two arrays was an ISI and in the second array one of the letters was occasionally altered. Basically, change blindness predicts that the participants should respond 50% correctly if they have a forced choice between change or no change – in other words, the subject should perform on chance level. Now, could a retrieval cue during the ISI, retrieve an object from iconic memory while the original array is no longer present? The data of Becker et al. (2000) indicate that this is the case. They cued at 16, 82, 149, 215 and 281 ms after the offset of the first array. The second array was presented 281 ms seconds after the first. If the cue came after 281 ms the second array and cue were presented simultaneously. The shorter the interval between the first array and cue was, the better the participants were able to detect the change. If the retrieval cue was given simultaneously with the second array, performance dropped back to chance, whereas cueing at 215 ms facilitated change detection above chance performance. With short stimulus to cue time, not only change detection improved, but even identification of the letters that changed improved significantly. This seems in line with iconic memory theory which states that the representation lasts for about 250 ms. These data showed that there is indeed more information represented or available than change blindness indicates and cueing attention to the changing items helps detecting and identifying the change.

However, another interesting question was raised in the article of Becker et al. (2000). There are at least two ways that can render iconic memory to become unstable. The first would be simple decay over time. The second possibility is that iconic information is overwritten when new stimuli fall on the retina. So, what causes the fast information loss in iconic memory, decay over time or overwriting due novel stimulus information? This question was addressed by Becker et al. (2000). They tested this with an experiment similar to the one described in the previous paragraph. In this experiment they did not vary the duration between the first stimulus array and the retrieval cue; this was always 16 ms. The time between the cue and the second stimulus array was manipulated. There were two possible scenarios. The first was: the cue was within the duration of iconic memory, thus performance is always much better than without cue. This scenario is consistent with the idea that the iconic image decays over time. The second scenario was: performance is better when there was some time between the cue and the test stimulus array. This scenario is consistent with the idea that an iconic image is overwritten by subsequent stimuli. This is consistent because, if the cue and second stimulus array arrive simultaneous the first array is overwritten. Hence, the cue cannot retrieve the pre-change objects. The results pointed to the second scenario: if the time between the cue and the onset of the second stimulus array was 0 ms the performance was not as good compared to when there was more time to process the letter from the first stimulus array. Thus, additional time between the cue and second stimulus can enhance change detection. These results were a bit counter intuitive, because they showed that more time between the pre- and post changes facilitated change blindness. The rationale behind this data is that the brain needs some time to transfer the iconic image from the visual sensory buffer to a durable store. If the cue is fast and the pre-changes are not overwritten, than there is time for storing an iconic image in a durable memory storage, hence change blindness is attenuated. Thus in our model (Figure 2) there is a representation available where sensory images are available, these iconic images are overwritten by all types of new information on the retinotopic location where new stimuli are presented.

If changes are stored in iconic memory they should be passed to a memory system that allows for detecting changes. Therefore, Landman, Spekreijse & Lamme (2003) examined the role of VSTM in change blindness, since it is a more durable store that represents bound objects. They used a single-shot paradigm to examine change blindness. Participants indicated whether the orientation of eight rectangles changed. Landman et al. (2003) observed the capacity of integrated objects that the participants could use for change detection. The ISI was 1600 ms in the first experiment. When cues were provided while the original image was on the display the capacity was near the maximum of 8 items. The capacity decreased to about 6 items when the cue arrived between 0 and 1500 ms after array 1 offset, which is higher than would be expected on basis of VSTM. Thus cueing between in the ISI increases the capacity of objects available for comparison with the second array. Thus like Becker et al. (2000), Landman et al. (2003) found that cueing in the ISI in a single-shot paradigm facilitates change detection. Additionally, they were able to replicate the finding of Becker et al. (2000) that cueing simultaneously with the presentation of the second array is not beneficial for change detection. However, what was at least remarkable was that cueing until at least 1500 ms was still beneficial for change detection. This is remarkable since such a long interval is longer than iconic memory theory predicts. They conducted a second experiment that showed that this was not due to afterimages of the rectangles.

Previously it was shown that changing pictures during saccades can induce change blindness (McConkie & Currie, 1996; Grimes, 1996). Landman et al. 2003 argue that saccades wipe out the iconic trace - see also Tatler (2001), who showed that humans can recall objects from a current fixation, but not from the previous one. Therefore they tested whether shifting attention was able to erase iconic traces like saccades do. They applied the same single-shot paradigm as was just discussed, however at some trials an erroneous cue was given to a target that was not changed. After this cue a valid cue could still be given. So, if shifting attention erased the representation of uncued targets the capacity resulting from these trials should be low. However, this was not what they found; the representation survived an invalid cue, since the capacity exceeded four; shifting attention does not cause a representation to become unstable as saccades do, therefore it does not interfere with change detection.

Data of a change blindness paradigm of Luck and Vogel (2003) showed that the number of items retained in VSTM was about four. Additionally they showed that these items are integrated objects. Since cueing was effective beyond the point that iconic memory could have facilitated the capacity of VSTM, it might be the case that the objects were more than a “simple” sensory trace.

In a fourth experiment of Landman et al. (2003) the role of feature binding was examined. They applied a single-shot paradigm as before, however, now either the orientation or the size of the rectangles could change. Cueing improved both types of changes even when both could occur. This showed that these features were simultaneously represented; hence the representation contains bound objects.

There seems to be a discrepancy between the results of Becker et al 2000 and Landman et al (2003). Most research shows that iconic memory has a time limited duration (+/- 250 ms) but an infinitely large capacity (Sperling, 1960) and VSTM has a longer duration, but is limited to about four integrated objects (Cowan, 2001). Thus either there is something wrong, or there is something else besides VSTM and iconic memory. To separate these issues an experiment was designed with two conditions (Sligte, Scholte & Lamme, 2008). These authors argue for a third short term store. The first memory storage they adopt is iconic memory as defined by Sperling (1960) with the change detection properties as indicated by Becker et al. (2000). Then they break VSTM in a *robust* part which has a capacity of 4 and a *fragile* part with a larger capacity.

To elaborate on these three different types of memory Sligte et al. (2008) designed a series of experiments starting with a study on the capacity of the three systems. A great deal of iconic memory might result from after effects of stimuli. The first experiment had a condition with 32, 16, 8 or 4 black and white rectangles, which has a strong luminance aftereffect. The second condition contained a gray background with isoluminant red rectangles, which should have a weak aftereffect. Within these conditions a cue could arrive directly after the first array (iconic cue), after 1000 ms (retro-cue), and simultaneous with the second array (post-cue). They showed that in the iconic cue condition the number of items was very large, but mainly for the stimuli with the strong luminance aftereffect and less for isoluminant stimuli. This showed that an aftereffect of light induced a strong iconic image that allows for very good change detection and very high capacity. With the retro cue a smaller capacity was found, but still much larger than the robust VSTM. Additionally, fragile VSTM capacity was not dependent on the strength of the after effect, in both conditions (weak and strong aftereffect) the capacity was equally high. With the post-cue, the capacity turned out to be four, just as VSTM theory predicts (Cowan, 2001). The largest capacity was found for retrieving objects from iconic memory if the after image was strong. A smaller capacity was found for the retro-cue, which could be used to retrieve a smaller number of objects than with the iconic cue but more than with the post-cue. Four objects could be stored in robust VSTM.

The previous paragraph indicated that fragile VSTM is not as fragile as iconic memory, for it is not dependent on the strength of the after effect. As an additional test, the stability of the two systems was examined, by masking. Any mask presented directly after the first array completely masked the iconic memory trace. This situation was more subtle when masks were presented just before the retro-cue. Here a light mask did not disturb the representation of the objects, however a mask containing objects did mask the objects in fragile VSTM. Additionally, they found that the more features an object had, the lower the capacity of the fragile VSTM in line with the (robust) VSTM (Alvarez & Cavanagh, 2000).

In summary, the storage of iconic memory is larger than that of fragile VSTM, which in its turn has a larger capacity than robust VSTM. There are two reasons to assume that objects in iconic memory exist of raw stimulus properties, whereas fragile VSTM stores bound/integrated objects. Firstly, iconic memory is very easily masked by any subsequent stimulus and fragile VSTM is only masked by objects. Secondly, fragile VSTM is not dependent on the strength of its after effect in contrast to iconic memory which is dependent of the strength of the after effect.

Landman et al. (2003) and Sligte et al. (2008) found that cueing between 1000 ms and 4000 ms after the presentation of the original stimulus array resulted in a capacity of VSTM that was larger then 4 items. Since the capacity of this memory store is larger than four and the duration exceeds iconic memory Sligte et al. (2008, 2009) and Landman et al. (2003) decided to differentiate between robust and fragile VSTM. This is remarkable because Becker et al. (2000) found that cues after about 215 ms did not enhance change detection and identification. Thus there seems to be a discrepancy between the findings of Becker et al (2000) and those of Landman et al. (2003) and Sligte et al. (2008). This yields the question: where do the different results come from? One possible option is: it seems that there is a kind of continuous transition from the sensory trace in iconic memory via bound features in fragile VSTM to robustly bound objects. There might be a moment in time when there is a process that integrates the iconic trace to a bound representation in VSTM. It is not tested what would happen if a participant is cued during the integration process. Perhaps the features must be firmly bound before objects can be retrieved from fragile VSTM. Alternatively, cueing during the binding process could possibly disturb the integration of the raw stimulus properties to bound objects. This can result in a model that demonstrates facilitated change detection with very early cues (<250 ms) as these retrieve information from iconic memory. Then there is a period where change blindness is likely since features are being integrated to objects and at this point iconic memory is not available anymore. Finally, if the features are bound in fragile VSTM cues will facilitate change detection again. This is an explanation that accounts for the data of Becker et al (2000) on the one hand and the results of Landman et al. (2003) and Sligte et al. (2008) on the other hand.

The results of Becker et al (2000), Landman (2003), Sligte (2008, 2009) led to a model of change blindness that incorporates three different memory structures. Every structure has it own properties that are different from each other. There is iconic memory that holds a vast amount of stimulus information that is extremely volatile to masking and therefore only retrievable for about 250 ms. Then there is a fragile form of VSTM where a large amount of stimuli are integrated into objects and more robust over time until about 4 seconds. Finally there is a robust form of VSTM where information is bound; here the objects are coherent over time, probably as long as these are rehearsed.

Physiology supporting change detection

Until now an overview of current literature has been presented that reviews cognitive processes that are engaged in change detection. During the last decade there have been some investigations into the physiology behind these mechanisms. The next section shows some of the components. However, as will be presented it is hard to find the exact locations in the human brain which are involved in the detection of changes in the terms of our model (Figure 2).

Now where in our neural system are change blindness and detection mechanisms represented? They should operate somewhere in the brain and influence the input of the visual information that is provided to visual areas in the brain. A recent study on the brain physiology using Event Related Potential (ERP) recordings showed some components involved in registering changes. Eimer and Mazza (2005) showed an N2pc contralateral to a change in the visual field. This is an early negative field potential which responded to a change of a face identity contralateral to the N2pc. Additionally they found a late P3 peak in the ElectroEncephaloGram (EEG). This P3 peak is thought to reflect the confidence of the participant. Eimer and Mazza (2005) concluded this from self reported confidence, the confidence correlated with the P3, additionally trials where subjects responded quickly also showed a relatively large P3. Thus although there is a P3 in change blindness paradigm, this is more related to other factors as the confidence of the perceived change. The previous mentioned data is not clear about the precise role of the N2pc. Therefore, Schanking and

Washer (2007) conducted similar experiments. They used dot patterns as stimuli; the change concerned the luminance of one dot. In the first task the dot was preceded by mudsplashes as in Regan et al. (1999), the second showed a brief blank between two dot patterns (see e.g. Rensink et al. 1997). The main interest was an N2pc component related to changes. Schanking et al. (2007) argued that two scenarios could occur. The first was that no N2pc would occur as changes were not detected. The second is that the N2pc is larger when changes are detected. If the N2pc only occurred during change detection this should have been a correlate of awareness, since it is only present when changes are detected. However, if the N2pc was weaker when undetected changes occurred compared to when change are detected, then the N2pc should be taken as a signal that correlates with a visual transient that is modified by attention. In the first experiment a contralateral N2pc to a detected change was significantly larger than the N2pc on change trials where the change was not detected. Thus the strength of the N2pc correlates with change detection. If no N2pc was present at trial without change, the N2pc might have reflected awareness. The second experiment found similar results, the N2pc was present in every change trial, probably due to the visual transient of the change. The N2pc was stronger on trials were the change was detected. Thus the N2pc is a necessity of awareness of the change that represents enhanced attention to the transient, but does not reflect awareness. A strong N2pc predicts change detection and a clear P3 indicates that a participant is confident that changes occurred.

The data on the N2pc indicated lateralized effects, corresponding with a change in the contralateral visual field. The N2pc resulted from the posterior electrodes. Before these electrophysiological studies a functional Magnetic Resonance Imaging (fMRI) was conducted in order to find which brain regions respond to change detection. This is very hard since there are many processes involved in visual search. From all these processes it is hard to extract the signal that represents change detection. Therefore, Huettel, Güzeldere and McCarthy (2001) developed a flicker paradigm of Rensink et al (1997) in order to extract the signal of change detection. The idea was that a lot of processes start on trial onset which are involved in visual processing of stimuli. These processes will show activation in the visual cortex and among these processes is the search for changes. Thus Huettel et al. (2001) developed an fMRI model to examine which activation correlated with the search process. If there was a distinct search process it should end when the change is found, whereas other visual processes continued to operate until the trial was stopped. Thus, Huettel et al. (2001) were looking for an event that started on trial onset and ended when the search was terminated (which was on the moment that the change was detected). The fusiform gyrus and inter parietal sulcus responded according the fMRI model that described visual search. Hence, these brain regions were active during the search process. Additionally, in frontal regions there was activation of the frontal and supplementary eye fields. Thus the striate/calcarine cortex responded to task onset and remained active during the entire trial duration. In contrast, the inter parietal sulcus, the fusiform gyrus, and the frontal and supplementary eye fields were only active while the participant was searching. Although many visual processes are active during a flicker paradigm, activation in the fusiform gyrus, IPS, and in the frontal and supplementary eye fields is related to the visual search for change.

In the former paragraph an experiment was explained that described the visual search process in a change detection task. At least as interesting is, what process starts when changes are detected, for such a process should reflect the areas involved in the detection of the change. To examine what processes reflect change detection Beck, Rees, Frith and Lavie (2001) contrasted trials where a change was detected with trials where the changes were present, but not perceived. They used changes in faces and outdoor scenes as stimuli. The fMRI contrast between activation on detected versus undetected trials showed cognitive processes involved detecting changes. This must have been related to change awareness since the task and stimuli were the same, the only difference could have arrived from whether a change was detected. This activity diverged in the ventral stream depending on whether the trial contained face or place stimulus. Perception of changes in faces resulted in enhanced activation in the fusiform gyrus, which is associated with face perception (Kanwisher, Dermott & Chun, 1997; Tempini, 1998). Place changes activated the fusiform gyrus as well, however more anterior and medial. This is located close to the parahippocampal place area (Epstein & Kanwisher, 1998). Other brain locations involved in the awareness of change detection were the bilateral parietal lobe and the right dorsolateral prefrontal cortex (Beck et al. 2001). There is difference in activity between changes that are perceived and changes that are not perceived. Hence, there might also be a difference between a trial with an unperceived change and a trial without change. The percept in an undetected change trial is the same as a in a no-change trial. Hence, the resulting activation comprises “low level” stimulus processing without awareness. In this comparison there was activation for faces only and in the ventral stream: fusiform gyrus, lingual gyrus and the inferior prefrontal gyrus. Thus for faces there is some stimulus processing, but without dorsal activity in the parietal lobe and dorsolateral prefrontal cortex this does not to lead to change detection.

The previous fMRI and EEG studies revealed the possibility that the parietal cortex is involved in the detection of changes. However, these techniques associate the parietal cortex with visual awareness of changes. Hence, there is need for a more causal approach to investigate the need for parietal cortex for visual awareness. In a study of Beck, Muggleton, Walsh and Lavie (2006) the involvement of the parietal cortex was examined using Transcranial Magnetic Stimulation (TMS). Rapid bursts of TMS were applied over the right or left parietal cortex in two thirds of the trials. On the other trials was no stimulation. Stimulation to the right parietal lobe decreased change detection performance. This showed that especially the right parietal lobe was involved in change detection. This is in accordance with previous findings in neglect patients (Pisella, Berberovic & Mattingley, 2004). Patients with neglect typically showed reduced change detection to the contralesional side of the visual field on a change blindness task. Patients with lesions in the right parietal lobe showed significantly larger change blindness (no patients with a left parietal lesion were included in the study of Pisella et al. (2004)). Although fMRI shows involvement of the bilateral parietal cortex in change blindness could this result only be replicated in the right parietal cortex using TMS.

The last paragraphs showed where changes are detected. If they are detected here, than they must have been coherent according the theory of Rensink (2000). Thus that can be a location for robust VSTM. To examine the location VSTM Sligte et al (2009) did an fMRI study to examine how fragile VSTM is represented. The main conclusion was that when V4 activity was strong the better the representation of the VSTM was. This indicated that there is a relation between V4 and the strength of a representation of a fragile VSTM object.

The following concluding remarks can be made about the physiology of change blindness. Change detection is signaled by a negative peak in the EEG after 200 ms at posterior electrodes. After 300 ms there is a positive peak in the EEG if the participant is confident about the change. These results are confirmed by fMRI data that showed enhanced brain physiology in the parietal lobe. There was also more activity in ventral regions (fusiform gyrus), but this only leads to change awareness if the parietal lobe is simultaneously activated. Virtual lesions and real lesions in the right parietal lobe impair change detection, thus this confirms the involvement of the right parietal lobe. As was noted the physiological location for change detection of faces is a little different than when place changes have occurred (Beck et al. 2001). Perception of face changes was indicated by physiological activity in the fusiform face area, whereas perceived changes in object location are more dependent on location near the hippocampal place area. This indicates that robust VSTM might be dependent on the areas that are specialized, like the fusiform face area for faces and the hippocampal place area for locations. Perhaps this can be elaborated by an experiment that shows that detection of a motion changes is signaled by activation in V5/MT. Fragile VSTM seemed to be dependent on V4 activity, which is still an early area in the visual steam and to some extend retinotopically organized. Iconic memory has been show that to be dependent on the strength of the after effects to some extend and it is likely stored before fragile VSTM in the visual cortex. Therefore the iconic memory in Figure 2 might be represented by neurons in the retinas, V1, V2 and V3. Fragile VSTM might depend on V4. Finally, Robust VSTM seems to be represented in specialized areas in the visual cortex beyond V4 in the visual streams.

The factors in change blindness and detection

In this article it has been discussed when change blindness occurs. It is a striking condition that not only happens in experimental settings, but also in real life situations (Tatler, 2001; Simons & Levin 1998). Mostly it occurs during a visual interruption like a blank screen (e.g. Renskink, 1997), a saccade (Grimes, 1996; McKonkie & Currie, 1996) or eye blinks (O'Regan et al. 2000). Although even when objects are added or deleted without a sudden visual transient (Simons et al., 2000), or mudsplashes appear or disappear simultaneous with changes, change blindness remains striking.

One of the most important factors for change detection is attention. It has been shown that when objects are naturally more appealing to people, change detection is strongly facilitated (Rensink et al., 1997). This is also demonstrated by the fact that drawing attention to the spatial location of the change enhanced its detection probability (Scholl, 2000; Cavanaugh & Wurtz, 2004). Also when people have a naturally large attention capacity available, change detection is improved (Pringle et al. 2001).

It appears that attention plays an important role as a mechanism that is able to read from iconic memory (Becker et al. 2000) or fragile VSTM (Landman et al. 2003; Sligte et al 2008; Sligte et al. 2009), see Figure 2. When stimuli fall on the retinas, their sensory traces are quickly overwritten by new stimulus information (Becker et al. 2000, Tatler 2000). Objects can be transferred to fragile VSTM where they can be stored as objects, the duration of this storage place is longer than iconic memory, but the storage space is more limited. As the objects arrive in fragile VSTM, they will be able to survive transients over the entire visual field (blank screens), but not to objects on the same location. If attention is not allocated to one of the objects, it needs "luck" in order to get to the robust VSTM, since it only allows for about four objects. In practice this means, if there are four objects to be seen changes will be detected. On the other hand if there are more than four items, the changing item will eventually be transferred to robust VSTM in the case of the flicker paradigm. However, this might also be due to an accumulation of information (Vierck & Kiesel, 2008). Therefore in scenes that are more complex than a four object scene, objects should be attended to in order to put them in a durable store that allows change detection.

Figure 2 shows a suggestion of how the visual information might flow in human observers. It shows that attention acts as a filter that selects attended stimuli, these stimuli are subsequently passed through to robust VSTM. When a stimulus arrives in robust VTSM it is coherent over space and time. Hence, the stimulus can be compared to a subsequent stimulus in order to see if it is altered. Figure 2 also demonstrates what the capacity of the memory stores are. The largest is iconic memory which is (almost) infinite (Sperling 1960) but the stimuli are not bound. A bit smaller is fragile VSTM in which many integrated stimuli are stored (Landman et al., 2003) and the smallest is robust VSTM with a capacity for four bound objects. Finally, Figure 2 shows the duration until the stimuli are lost from the memory structure, iconic memory is preserved for about 250 ms, fragile VSTM for plus minus 4000 ms and the robust longer than 4000 ms. Thus a cue before 250 ms retrieves from iconic memory and cues after before 4000 ms gets objects from fragile VSTM. If a cue is presented after 4000 ms the cue is probably redundant, since either the memory is lost or the object is coherent anyway. Figure 2 also represents a suggestion of where memory stores are represented in the brain. Iconic memory is thought to be represented in the retina, V1, V2 and V3. Fragile VSTM depends on V4. Finally robust VSTM as used for the detection of changes is stored in areas that have some specialization and are beyond V4 in the visual streams, for example face changes are detected in the fusiform face area.

Although change blindness has demonstrated quite some details about the transition of stimuli through different memory structures aided by attention, there are some issues left before a proper model can be built. As was previously mentioned, the results of Becker et al. (2000) show that cues do not improve change detection after the limits of iconic memory (250 ms), however the data of Landman et al. (2003) and Sligte et al. (2008, 2009) demonstrate that cueing from 1000 to about 4000 ms results in an enhanced capacity beyond four items that shows that more objects are available which allow for change detection. Therefore the time course of cueing 0 ms and 1000ms should be investigated. If the unbound features in iconic memory must be bound in order to arrive in fragile VSTM, then change detection is unlikely short after 250 ms. After a while the features are integrated into objects, then change detection should improve as the features of an object are bound together. A second detail that deserves some elaboration is: is it possible for a stimulus in iconic memory to skip fragile

VSTM and go straight to robust VSTM? Currently, Figure 2 shows that attention and memory are completely different psychological constructs. However, in a recent study evidence has been gathered that spatial attention and readout from iconic memory might rely on similar neural processes (Ruff, Kristjánsson & Driver, 2007).

To summarize, change blindness paradigms have yielded interesting data about how stimuli are processed throughout different types of memory. Additionally, they have shown why attention is so important to find changes in scenes, stimulus arrays etc. However, more studies need to be conducted to create an accurate model of the role that memory and attention play in change blindness. These studies should clarify even more precisely how the information flow is. Secondly, data should clarify whether spatial attention and readout from iconic memory are truly different. Thirdly, these studies should examine what happens between iconic memory and fragile VSTM. Finally, an investigation into the neural processes could demonstrate what regions and at which times are involved in processing changes in our daily world.

Conclusion: change detection is mediated by a cooperation between memory and attention

In order to illuminate why people can be blind to salient changes in our environment we developed a model that illustrates the factors that play a major role. We argued that objects must be in the robust part of VSTM in order for people to perceive that the object has changed. However, stimuli that fall on our retinas will not always end up in robust VSTM. Attention can help to filter the large amount of stimuli present in iconic memory or fragile VSTM. Attention must be drawn in time to these very short term stores in order to select the changing item and shift it to robust VSTM. Thus, attention selects the objects in iconic memory and fragile VSTM and will transfer the selected items to robust VSTM; hence attention ensures that changes are detected.

Change blindness has revealed that there is no complete internal representation of surrounding scenes. In order to detect changes there must be a good coherent representation of visual stimuli; therefore attention must work in unison with iconic and fragile VSTM. Stimuli should be attended to in order to shift them into the more durable robust VSTM. Stimuli which are present in robust VSTM allow for the detection of changes. Therefore we can conclude that change blindness is well suited for research topics like memory and attention. The change blindness paradigms provide us with tools to examine the interface between attention and memory and potentially between different memory stores. It shows when and how attention is allocated in order to retrieve objects from short term stores and transfer them to relatively long term stores. Therefore the paradigm of change blindness allows us to test the conditions under which attention is successfully allocated. Change blindness might reveal information about the interface between sensory buffers and short term memory. Eventually it might tell us how humans get conscious of their changing environments. Although some changes in the environment are noticed, attention can guarantee that objects are stored in the robust form of VSTM, here objects are coherent over space and time in order to overcome change blindness.

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