Cognitive Neuroscience and the Study of Attention

- Happily ever after? -

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1 Introduction

Attention is one of those terms that almost everyone readily uses in everyday language. Our whole culture is riddled with multiples uses of this term in countless sayings and common parlance. In fact, a quick search on the internet (using "Google") reveals over 14.500.000 websites containing the word "attention". Obviously, this concept seems to be of central relevance and importance. Surprisingly, this use seems to be far exceeding our actual knowledge about attention as a concept: As a rough measure, "Psycinfo" contains only 67857 articles with the keyword attention (compared, for example, to the term Perception, where only 2.450.000 websites mentioning the word go with 150419 articles in Psycinfo which is a far better ratio in this – admittedly – coarse measure). Moreover, most of these articles in Psycinfo use the concept of attention in a rather fuzzy way and use the term as a mere label, not contributing to our understanding of attention, but often dealing with disorders like ADHD. As puzzling as this ridiculous discrepancy may be, it illustrates a fundamental point about our dealing with this concept and maybe even something about the obviously elusive nature of attention itself: Our use of the term far exceeds our understanding of the concept, still most people – and even most researchers – use it in very versatile ways, not warranted by anything but our intuitive notions of attention itself. Yet, people who are bothered by this state of affairs and address it explicitly as a crucial problem are rare exceptions like Pashler (1999).

As he pointed out, this problem hasn´t been overcome in over 50 years of intensive research on the topic of attention but keeps lurking and hiding at the very fundaments of the field itself. The long-term results are devastating and principally not resolvable, even with the most sophisticated methods, as the matter of definitions and concepts precedes the generation and interpretation of empirical data. The field still lacks a consensus over fundamental terms, concepts and definitions; researchers are still setting out with "their" notion about attention, with all the hidden assumptions and implications that come with the use of an implicitly defined concept. If discrepancies with the findings of other scientists in the field occur (which usually do, given this use of concepts), they will most likely be attributed to the nature of attention itself and frantically be attempted to resolve on empirical grounds. But this attempt is futile, as it most likely results from a hidden disagreement in basic premises (hidden behind the use of the same term with different meanings). In addition, given the - in fact - rather elusive nature of attention compared to other and more directly observable concepts of psychology, everything is well set for an almost limitless and total confusion, leaving everyone who get´s in touch with those issues broken, troubled and sad. But let’s not get too philosophical here:

The purpose of this paper is to point out some of the problems that most likely arose from the conditions discussed above, the – in general – unsuccessful attempts of cognitive psychology to resolve these problems and to review the attempts that have recently been made to answer these nagging questions by research in cognitive neuroscience, as well as to evaluate these attempts and the prospects of this new approach in general – with a particular emphasis on neural correlates of attention.

In an ideal world without deadlines and grades, this would actually be the adequate level of this paper. Also, this would not be a final paper, but an article.

However, we don´t live in this world and the existing literature is huge; This is, why it´s beyond the scope of this paper to address all relevant findings of cognitive neuroscience and recent cognitive neuroscientific models of attention. Regarding the growing literature in this area, the purpose can´t possible be to provide a comprehensive review of this literature. Therefore, I tried to do my best by citing some of the most relevant models in the neuroscience of attention in an exemplar fashion, illustrating possible ways in which cognitive neuroscience can relate to cognitive psychology, ways of helping by illuminating the problems from a new perspective with new methods, as well as pointing out, which principal problems still remain and aren't resolved by this innovations.

I also tried my best to make sense of the empirical findings that I encountered in the literature... especially in the field of attention, one encounters so many conflicting findings and so little agreement on basic issues, that one could lose faith in science and leave the field altogether, deeply frustrated.

Before dealing with more concrete and detailed issues, let me briefly address the question why it could be useful to approach attention with methods of cognitive neuroscience in the first place. Considering the pain and effort and costs that even a simple study in this field requires, this question is valid: Why bother with cognitive neuroscience at all? What can it possibly show beyond the results that psychological approaches have yielded so far?

The answer is relatively simple. Attention is presumably a highly complex phenomenon with mechanisms hidden in the computational architecture of the brain. It could be simply inappropriate to try to tap attention on the rather superficial and coarse level of studies that use merely behavioral response measures like reaction time, accuracy of performance and psychophysical thresholds. The use of the methods of cognitive neuroscience promise to provide new level of analysis beneath and beyond this level, potentially uncovering the "true" nature of attention as working in the brain and nailing down hard empirical facts about attention.

These hopes are maybe not set too high: Exactly this way obviously worked out in a related field of cognitive psychology: Mental imagery. As attention, mental imagery as a construct is also rather elusive: Everyone has a subjective experience of the phenomenon, but an objective, scientific approach is not easy. As a result, a fierce debate was raging in the field for decades: The so-called "imagery debates" (see Kosslyn, 1994). For all this decades, it was highly disputed if something like mental imagery exists, and if it exists, how it operates and what implications derive from mental imagery. On one side were advocates of mental imagery and it´s use for information processing and representation, with Kosslyn being their most prominent proponent. On the other side were people like Pylyshyn, doubting every single claim by Kosslyn et. al. and proposing alternative interpretations of the findings that were more in line with his ideas of propositional representation and processing. No side was willing to give in and none of the major issues could be resolved on empirical grounds. In fact, this was not possible, using only behavioral response measures: As already Anderson (1978) pointed out, all behavior can be potentially generated and emulated by different underlying processing mechanisms (by making tradeoffs and adjusting model parameters) , which is why those behavioral studies are in principle inadequate to discriminate between different theoretical models that could account for the behavioral performance.

Decisive breakthroughs came only by using the physiological methods of cognitive neuroscience in mental imagery studies – largely supporting most of Kosslyns claims and effectively resolving the imagery-debates. For example, it could be shown that even areas down to V1 can be recruited and engaged by visual mental imagery, suggesting a similar processing as in perception. Through cognitive neuroscience, mental imagery has gone a long way and many elusive issues regarding mental imagery could be clarified. The once fuzzy construct is now being thoroughly studied and very precise hypothesis and algorithms about the functional role of imagery in perception itself can be tested, revealing very exciting findings (Kosslyn, 1994).

Therefore, the hopes are high: Like in the case of imagery, the use of the methods of cognitive neuroscience could potentially bring “salvation” to the long-troubled field of attention-research. Can it? At least, the study of attention is currently en vogue in cognitive neuroscience.

2 Attention in cognitive psychology

Interestingly, one is rather hard pressed to find a current study that is done in an “old-fashioned” way, relying solely on behavioral response measures and explicitly addressing one of the classical problems of the field (as early vs. late selection, nature of filters or the like).
Considering the fact that this kind of study was once flourishing, filling psychological journals year after year, one can wonder what happened to the field since then. Did people come to the conclusion that it is futile to merely rely on behavioral reponse measures, did the researchers just lose interest in this kind of studies, became frustrated or did they actually jump on the bandwagon of cognitive neuroscience? Speculation about reasons aside, this illustrates the massive impact of the apparent paradigm-shift that took place in attention-research and the way we conceptually deal with attention in research.
In any case, this section first deals with a brief outline of the history of attention research in cognitive psychology that led to this development. In a second part, we will discuss some of the most important and nagging problems that were spawned, but not resolved in this history.

2.1. A brief history of attention research in psychology

This paragraph about the history of attention research is also – necessarily – very coarse and oversimplified mainly due to limitations in space. The “real” story was of course not that simple, but for our purposes, this overview serves merely as an advanced organiser and for that, it should be in fact acceptable to restrict and concentrate our review on the main figures and the essential milestones in attention research.
Systematic scientific research comparable to that done by cognitive psychologists in the 20th century was – after some preliminary findings of introspective psychology – pioneered

particularly by William James in a more theoretical and by Hermann von Helmholtz in a more empirical way in the late 19th century. After establishing reliable basic findings like the fact that directing attention to a particular region on the screen without moving the eyes, the whole field was basically abandoned due to the advent of behaviorism in the early 20th century. The study of attention as well as the whole concept of attention was far too "mental" and fuzzy for behaviorists like Watson who wanted to re-found psychology as a hard science and tried to get rid of all introspectively defined concepts in order to do so. The study of the prediction and control of behavior dominated in psychology, the study of the mind was deemed as unscientific, unimportant and also not interesting. Therefore, developments in the field were stalled for almost 50 years.

It was only with the fall of behaviorism as the leading paradigm of psychology in the 1950s and the parallel rise of cognitivism that the scientific study of attention was revived within psychology and experienced a thriving renaissance. In fact, attentional effects and attentional research was one of the paradigmatical cases that exemplified the shortcomings of the behaviorist approach, justifying cognitivism: For hardcore behaviorists, the behavior of an organism is under environmental stimulus-control, behavior is a function of the stimulus. The early cognitivists were able to show that behavior is in fact a function of the attentionally processed stimulus, and that attention can lead to differentially processings of the same stimulus. In other words, it was shown, that one has to take the modulatory effects of attention on the processing of stimulus into account, if one wants to accurately predict and control the behavior of the organism which made it impossible even for behaviorists to totally ignore this "mental" processing level.

Soon, many of the empirical findings and phenomena that hold true until today were discovered – even despite poorly developed methods, for example the findings of Cherry (see Cherry, 1953) about the capabilities of people to attend to two different sources simultaneously and the (stimulus)-conditions under which this was possible.

Another milestone was achieved by Broadbent (Broadbent, 1957) who summarised most of the empirical findings known until then in a simple and compelling mechanical bottleneck-model in which he emphasised the channel selection properties of attention in information processing.

Speaking in deliberate exaggeration, it was basically all downhill since these promising outsets. The field never regained the coherence of this stage. Sure – there was a rapidly growing body of empirical findings. But unfortunately, most of these findings were conflicting and proved to be essentially unresolvable by subsequent studies, even though the behavioral methods were steadily improved (Introducing shadowing, dual-task-paradigms, pin-point responses, etc.) and new modalities (like vision) were explored. Shortcomings of existing models that tried to account for empirical data were uncovered in order to replace the model a new one that had other shortcomings – which led to a inflation of terms, models and concepts.

The malice began with the alternative model of Deutsch & Deutsch (1963) who essentially used some properties of the cocktail-party phenomenon to challenge Broadbents theoretical notions and introduced a “late selection” model, where the attentional selection is basically a matter of memory-processing and response-selection. The arguments that ensued after this challenge led to an avalance of empirical studies and findings, but were never resolved.

New models were introduced like the attenuated filter-model of Treisman (1964) or the late-selection account of Posner (see Posner, 1999). New concepts gained importance like capacity and capacity limits or processing resources. Some of these models tried to integrate a physiological dimension or were revised like the feature-integration model of Treisman, assigning attention a different role in information processing. All industrious experimenting and ingenious theorising could not hide the fact that no lasting progress in the field was achieved, especially in comparison to other rapidly progressing fields of cognitive psychology like memory or perception. In fact, the never-ending stream of new models (spotlight, zoom-lens) was accompanied by the fact that attention more and more assumed the role of everybody's magical theoretical joker: Everything that couldn´t be accounted for otherwise was explained by attention. A striking example of this tendency is Treisman who tried to resolve another long-nagging problem of cognitive psychology, namely the binding-problem, en passant by assigning this feature-binding role to attention – regardless of how valid or invalid her feature-integration approach itself may be in itself.

According to Pashler (1999), the study of attention in cognitive psychology reached practically a dead end in the late 1980s and early 1990, with an abundance of questions, problems, models, concepts and issues without the capabilities to resolve or compellingly decide about the validity of any of them. Behavioral measures like RT and performance ultimately were evidently not enough to overcome the problems that troubled the field.

In parallel, with the invention and use of new methods, a new field came into existence: Cognitive neuroscience. Attentional researchers readily turned to the methods provided by this field, trying to use them, throwing them at the problems in attention research in order to approach the old problems that caused trouble for so long from new angles.

This is the current state of the field. In hindsight, this turn to cognitive neuroscience provides not only a chance, but is also a risky undertaking: As Pashler pointed out, not only were the findings in the original field conflicting, our theoretical notions were as well discrepant – there was never an explicit agreement about fundamental terms and concepts. This problem is more subtle, but causes imminent danger. Without an a priori clear idea what one is looking for, one can easily get lost in the complexities of the brain and the technical challenges and details of the used sophisticated methods and techniques without being able to resolve any of the questions that one set out to answer but instead getting again overwhelmed by even more complex and conflicting findings. So far, it is not entirely clear, how real this danger is – but one should at least be aware of the fact that cognitive neuroscience is not necessarily only a blessing but could as well turn out to be in fact a double-edged sword.

2.2. Classic issues in attentional research

The issues presented here largely derive from Pashlers review (1999). Research on attention in cognitive psychology was most successful in generating questions and problems. The studies reported throughout his book are rarely conclusive in respect to the issue they wanted to address and it seemed that Pashler was hard pressed to interpret the empirical findings in a coherent way. Maybe that´s where his rather pessimistic notion that no one knows what attention is derives from. What a mess. Over 100 years earlier, William James put forward that everyone knows what attention is. What was the progress after decades of intensive research? Definitely not in the answers, in the understanding of the nature of attention. Maybe it lies in the emergent understanding that the nature of attention is extremely complex and elusive. In fact, reviewing the attentional literature, one has a very hard time finding a question that was ever definitely answered in a satisfying way after it came into existence. Also, one doesn´t find much agreement on anything major within the field.

Therefore, the main accomplishment of the field was to generate issues which is in itself also a creative act. Let´s appreciate and honor this accomplishments by reviewing some of them before we deal with cognitive neuroscience in the next section, which promised and is appointed to go beyond that and could finally enlighten us about the nature of attention itself.

Again, spatial constraints prevent a more elaborate discussion of this issues. A brief outline has to be sufficient for our purposes. At least the following issues were highly debated in the field:

Early vs. late selection

The issue of early vs. late selection is THE single most classic problem in attention research since the cognitive revolution, it somehow relates to most problems in the field like if attention selects on the basis of object or features like spatial location and divided the field for decades. The early vs. late problem is not defined in terms of absolute points of time at which selection occurs per se (even if correlated to time). The assertion that attention influences information processing already on a perceptual level (by selecting the input) is emphasised by all instances of the family of early selection models like the classic Broadbent-Filter Model (Broadbent, 1953), tied with a whole bunch of implied assumptions like serial processing or strict processing limits. Conversely, late selection theories like those that were proposed by Posner and the prominent Deutsch & Deutsch model (Deutsch & Deutsch, 1963) share the claim that pre-attentive processing is going on for a long time in the brain and the selective nature of attention is on the response level, controlling which information is further processed and gets access to awareness, memory and impact on behavior. Despite all the research that arose from this debate, it was never resolved in cognitive psychology. Just to the opposite: Matters became more and more complicated until most people were content with the notion that the questions was oversimplified and ill-framed in the first place (Pashler, 1999). Re-interpretations of the data at hand reject strict interpretations of models of early- and late selection as well, but the refined flexible central processing model to account for the data brought forward by Pashler (1999) is maybe not easily testable on empirical grounds, could be unfalsifiable because there are just not very many patterns of empirical results that could – in principle – disconform the model, immunizing it and leaving it with very few empirical content (by Popperian standards).

The “nature” of attention

Related to the early/late-debate is the issue, what attention is in the first place. What conceptual model best decribes and fits the properties of attentional effects that were empirically shown? As the empirical findings were often conflicting in the history of research on attention, theorists had a hard time trying to integrate all these findings. Therefore, the invention of new models and metaphors of attention was always a blooming business. Among others, Attention was conceived as a filter, a bottleneck, a spotlight, a zoom-lens, as a limited processing capacity system and as processing ressources, always emphasising different aspects of attention that are implied by the respective models (See Pashler, 1999). For example, the used theoretical model determines, if attention is best described as a selection process, vs. a filtering process vs. an attenuation process vs. a process that highlights and amplifies certain aspects in cognitive processing. Some of these models are in the end formally equivalent, making a distinction between them arbitrary, but some of them aren´t and it makes a big difference which model one uses to fit the data, for example the difference between switching a rigid filter vs. continuous sharing of capacity.

Interestingly, the invention of theoretical models seems to be strongly influenced by the methods that were used to come up with the empirical results. As early attentional research focused on the modality of audition notions of filter- or bottleneck models were prominent. Immediately after the main focus of attentional research switched from audition to paradigms of visual attention, different kinds of models were created: The Spotlight- and Zoomlens-models of attention. Theoretical modeling in attention research seems to be strongly influenced by the studied modalities and the methods used in these studies.

The number of attentional mechanisms

This immediately begs the question if there is just one common mechanism that underlies attentional effects. Most likely, attention operates differently in different domains, rendering the search for the unified attentional mechanism futile. Besides that, it also remains essentially unclear, if there is just one bottleneck of attention (if there is one) or if attention operates on multiple levels of cognitive processing.

Probably, there is no special attentional mechanism at all. It´s entirely possible, that “attention” is just a convenient label for a multitude of effects that derive from the concrete processing architecture of the different neural systems like perception, memory or action. For example, “visual attention” was often studied, using a visual search paradigm. The effects that were found there don´t need to reflect the workings of a general attentional mechanism, but could also be inherent properties of the processing that occurs by the demands of visual search tasks. Moreover, it´s possible that attention is best described as an emergent property of the simultaneous activity of different interacting processing systems.

Also, it´s not entirely clear if selective attention and divided attention are really different processes, as claimed by some. A closer look at the operationalisation of the tasks used to study these phenomena suggests that the main difference lies in the instructions for the subject and the terms that are used to describe the performance of the subjects (Failure of selective attention = capability for divided attention?), rendering this distinction as superficial and needlessly confusing.

Much was speculated over these question in past decades. Of course, no one really knows so far.

Selection for features, objects or spatial locations?

Assuming that attentional selection of stimuli exists, it remains unclear, on what grounds this selection operates. The most popular suggestions in the literature so far were: On the level of objects, on the level of features of objects and on the level of spatial locations. Of course, in a natural situation, all these criteria coincide: An object consists of features and is in a certain spatial location.

This question is of major theoretical importance for attention research: A selection on the level of objects would support the notion of late selection after the identification of the stimulus (linking attention to

object-recognition, which comes with a lot of hidden theoretical assumptions), whereas a selection on the level of features would favor an early selection theory, where attention is important to identify stimuli. Showing a selection for spatial location, would particularly support the “spotlight”-model of attention. The importance of the question is reflected in the effort that was put in the cause to experimentally differentiate between these criteria that are confounded in everyday experience.

This effort was successful – proponents of all three notions were able to obtain empirical evidence that supported their notion. Unfortunately, this evidence in favor of one of these selection criteria is incommensurate and was generated in different experimental paradigms with different instructions, different (and exclusive) operationalisations of attention, etc.

Again, this question remained unresolved.

Automaticity and the fate of unattended stimuli

In a similar fashion, the question if automatic processing of stimuli without the need for attention is possible, relates to the early vs. late issue. Strong evidence for massive parallel processing without any need for attention would support the notion of late selection. Also, unwanted interference like that shown in the Stroop-task would support automatic processing and late selection. Alternative interpretations of the data are – of course – always possible. Evidence for late selection could be interpreted as an indication of a parallel automatic processing system independent from attention (Fournier & Shorter, 2001).

The data that could decide this question in support of one or the other position is not very coherent. It´s not easy to come up with a behavioral task that could show if a stimulus was processed or not without interfering with the task itself, possibly altering important characteristics of the process. Measures that are taken after the process are polluted with memory-effects.

Therefore, it remains unclear if a stimulus can be processed without attention.

The nature of resources

Processing resources, the “theoretical soupstone” became very attractive for a lot of theorists in the field. There are some theorists who conceptualise resources just on formal grounds, not bothering with the physiological substrate. Others feel more comfortable by grounding these mysterious metaphorical batteries of the mind in the brain. There are many things in the brain that could possibly be conceived of as resources: Blood, neurotransmitters, glucose, hemispheres, etc.

Unfortunately, these notions were largely just speculations without convincing and compelling empirical support.

The relation of attention to other functions

When attention research started out in the late 19th century, the concept of attention was closely tied to the concept of conscious awareness. It was conjectured, that attention is a prerequisite of conscious awareness of stimuli on the one hand and necessary to protect consciousness from an avalanche of unorganised sensual stimulation threatening to overwhelm consciousness on the other. Empirical support for this initial notion is indeed sparse. There is no definite evidence for such a disorder on neuropsychological grounds, even though some consider disorders like autism or schizophrenia as an attentional problem of filtering; there are many alternative hypothesis about the nature and causes of these illnesses which are – by the way – not very good understood by themselves.

With time, it was shown that attentional processes don´t necessarily involve awareness, but it remains unclear, if attention is a necessary or sufficient condition for conciousness or not, as well as other aspects of this relationship. Our knowledge about the relationship between attention and other cognitive processes besides consciousness is often even more fuzzy.

It would indeed be very important and highly useful to know the specific relations between attention and other functions like motivation, emotion, memory, consciousness, perception and action.

There are apparent relations to all kinds of other processes in the brain, but their concrete nature remains unclear so far – which is no big surprise, given the little agreement on the nature of attention itself.

In conclusion, there are a lot of controversial and important issues to be resolved in the field and it would already be a big feat, if cognitive neuroscience could adequately address and contribute to the resolution of just some of them.

It would also be very enlightening to know if the apparent disagreement on so many issues to such an extreme extent (compared to other fields) mainly reflects our premature and lacking empirical knowledge, poor theoretical modeling and understanding or the elusive nature of attention itself.

3 The cognitive neuroscience of attention

This section lies at the core of the paper at hand. In a first paragraph, I will lie out the main contribution that cognitive neuroscience brought to the field: It´s methods. And some of the basic issues that it wanted to address with them. In a second paragraph, I want to review and discuss some prominent models in the field that build genuinely on findings obtained with these methods. After that, some general effects of attention on cognitive processes are illustrated, as well as discussing some of the old questions in the field in the light of findings in cognitive neuroscience research. Finally, remaining challenges for the field are outlined.

3.1. Basic methods and basic issues

As mentioned above, the impact made by cognitive neuroscience on the study of attention was largely due to the use of new and sophisticated methods. It makes sense to lay out these specific methods in detail and discuss, which questions and issues they are able to address.

The toolbox currently available to by cognitive neuroscientists to study the brain and the behavior generated by it is - in fact - very rich, versatile and impressive. Every single used method is especially suitable to study a certain aspect of brain and behavior. Also, every method has distinctive inherent drawbacks, which is the reason why there are different methods necessary. Most widely used in attentional research are:

Neuropsychological methods: Here, interesting behavioral deficits are interpreted in terms of the disorders and lesions in the brain by which they were most likely caused. The interpretation of “clinical” behavior to draw conclusions about the underlying brain functions is in now way restricted to cognitive neuroscience but has very long history in psychology and biological sciences in general. Still, these methods are used by cognitive neuroscientists to get a first idea about the potential functions of brain areas before using more fine-grained methods and to construct functional theories on a molar model, integrating large bodies of empirical evidence.

The inherent drawbacks of this methods are well known and limit their use: Neuropsychological evidence is largely anecdotical, as the patients that are observed were the victims of different illnesses and accidents that are interpreted post-hoc. This also implies, that the obtained data is correlational in nature, which means that causality can´t be established using these methods. Also, the reported lesions in the brain are most-likely not easy to localise and not restricted to single areas, making it difficult to attribute functions to specific brain areas, in most cases allowing only very coarse conclusions about whole lobes or even hemispheres. Finally, there are problems in the logic of the method itself: The fact that a function disappears after damage to a certain brain area or a disorder in a function arises after the brain damage doesn´t necessarily imply that the function was controlled by this brain area if the behavior was intially generated by an interacting system of brain sites.

Efforts are made to overcome these problems by performing controlled and systematic lesion studies in animals, which is especially useful if there is an adequate animal-model for the human behavior at hand.

Yet, despite all this known problems with the method it´s common to discuss certain neuropsychological disorders in terms of attention or attentional deficits, especially in the guidance and direction of attention. Exemplar and well-known cases discussed in the context of attention research are **Balint´s syndrome** and **hemifield neglect**, where patients suffer from very intriguing patterns of behavioral deficit that commonly arise after damage to certain brain areas (for example, the right parietal lobe) and can´t be explained by perceptual problems, why they are attributed to be attentional problems, as problems in deploying attention to a spatial location and a biased competition, causing extinction (see paragraph 3.2.)

A more conceptual main critique of the use of this method in attentional research remains: On the one hand, attention is used as an explanatory term to explain these disorder. Without a clear understanding of the nature of attention itself. On the other hand, these disorders are cited as reference to illuminate the nature of attention. This is very close to circular reasoning.

Psychophysical methods: These are similar to the neuropsychological methods in respect to time: They are also around very long, long before the advent of cognitive neuroscience, but now widely used in contexts of cognitive neuroscience. The two most widely used psychophysical methods are scalp-recordings from EEG and MEG, interpreting the electrical and magnetic cortical activity. The advantages are clear: These methods allow to monitor brain activity in the healthy subject in a non-invasive way, allowing to monitor information processing online and in experiments. Also, it´s very useful to measure the electric activity of the brain directly, in contrast to the reliance on proxies. Further, they allow an excellent temporal resolution, down to the millisecond-range and below.

The main drawback in the use of EEG and MEG is, that they have a very coarse spatial resolution. The recorded scalp-potentials are essentially summed potentials, generated by the apical dendrites of thousands of neuronal columns, mediated by bone matter and the dura, making it very hard to localise the generators of the electrical signals.

In research on attention, these methods were pioneered by Hillyard (see for example Hillyard, et. al. 1995). Because of their excellent temporal resolution, they are useful to trace the flow of information processing in the brain, revealing the time-course of this processing. Therefore, for example, they can be used to assess the validity of early and late selection-theories of attention. Attentional effects change the amplitude and latency of the recorded brain potentials in a systematic way, allowing to draw conclusions about the influence of attention in different stages of processing, making these methods highly relevant to address questions in attentional research that concern all kinds of time-related issues.

Neuroimaging methods: Especially PET and fMRI are widely used in cognitive neuroscience. These methods are very complex – the general idea is to introduce or use markers (radioactive or not) in substances that are metabolised by the brain in cognitive processing and monitor and record the distribution of the activity of this marker. The brain is very sensitive for metabolic demands on a local level, allowing a very high spatial resolution of these methods. The advantage is obvious and analogous to the use of EEG-methods: The methods allow to systematically study (using healthy, normal subjects) and precisely localise activation changes in brain tissue, covariating with the performance of cognitive processing, giving a high-resolution mapping of what is going on in the brain.

The method has five main disadvantages: First, the measure of cortical activity is not directly the electrical activity of the brain, but metabolic activity / bloodflow with is a proxy for synaptic activity which is a proxy for electrical activity of neurons. Underlying interactions or differential activation are not reflected in this one-dimensional measure making it not unambiguous, what activation means in a concrete case. Moreover, fMRI and PET suffer from a very poor temporal resolution. The metabolic system has a certain inertia, which doesn’t allow a better resolution then around 1000 ms, effectively complementing EEG-methods.

Also, the potential knowledge that is obtainable with these methods is largely restricted to determining, which brain areas are active, localising functions, but it´s not possible to determine, how these areas work.

The quality of the data is again correlational, associating the activity of brain areas with certain behaviors and associating the activity of brain areas with the activity of other areas. An invasive independent variable to establish full causality is still lacking.

Finally, in the most widely used form of neuroimaging studies, there is no measurement of activation per se, but differences in activation to other conditions, using subtractive methods. As the brain is always active and processing, it can be hard to come up with adequate “control” conditions to subtract from.

Nevertheless, these methods are especially useful in attentional research to address a wide variety of open questions. First and foremost, the question if there are common or different attentional mechanisms – determined by common or different areas that vary in activation levels covariating with attentional demands (see Downing et. al., 2001) or the question, which areas are affectable by attention at all and at which level of processing, revealing the circuitry that subserves in attentional control and execution (see Kastner et. al, 1998).

Another question that could potentially be settled deals with the issue if there is a selection for objects, locations or features, which is hard to differentiate using only behavioral measures, but can be probed by assessing the differential activation that arises from adequate experimental attentional conditions (Kastner & Ungerleider, 2001).

Easily, the relationship between different processing systems like the relation between memory and attention can be illuminated by the use of neuroimaging (Gode Fockert et. al., 2001).

Finally, the question about the fate of unattended stimuli and the related question of automatic processing can be assessed with neuroimaging measures of activity, as these don´t interfere with cognitive processing itself (Driver & Frackowiak, 2001; Rees & Lavie, 2001).

In total, the potential value of neuroimaging methods to settle a lot of troubling questions in the study of attention is strikingly obvious.

Electrophysiologal methods: These are mainly single-cell recordings in behaving, awake monkeys (for a review, see Maunsell & McAdams, 2001). The advantages of this kind of methodology are straight-forward: Single-cell recordings provide a direct and spatiotemporal precise measure of the electrical activities of neurons at a cellular level. Therefore, this method is very sensitive for any influences on the level of electrical activity of neurons.

Drawbacks of the method are that they normally can´t be used in humans (for ethical reasons) and therefore have to rely on animal models, most often macaque monkeys, which could give a biased picture of processing if results are generalised from monkey to human processing (which is usually the case).

Moreover, single cell recordings are only capable of assessing the local electrical activities of single neurons, only allowing a very restricted look at the activity on this level. If the processing is done involving interactions of larger and distributed networks of neural populations, the detection of these interactions is largely beyond the capabilities of this method.

Still, electrophysiological methods have already been useful for attentional research, especially in research on visual selective attention.

Treue (see Treue & Maunsell 1996, Treue & Maunsell 1999, Treue 2001) extensively studied attentional effects in the dorsal processing stream, Reynoldts did so in the ventral stream (see Reynoldts et. al, 1999, Reynoldt & Desimone, 2001).

Also, Desimone & Duncan (1995) used this methodology to build their widely-renowned "biased-competition" model of attention.

Like no other currently available method, it allows the study of the modulatory effects of attention on the response-properties and tuning-curves of receptive field of neurons itself, revealing much about the nature of attention on a cellular level, giving insight in the concrete mechanisms, a grip on the specific and physically real workings that attention can to in neural tissue; supporting the notion that "attention" is maybe a basic property of neural tissue, not necessarily involving specially devoted circuitry.

The insight in the nature of attention that derived from the use of this particular method so far is quite encouraging.

Promising future methods: As outlined, all methods in use suffer from characteristic drawbacks that limit the knowledge that we can generate with them. This reason keeps the development of methods going. Two methods that certainly will become extensively used in attentional research are TMS and multi-electrode bundle recording.

TMS (Transcranial-magnetic-stimulation) allows to influence neural firing in a non-invasive way and to knock-out the neural activity in circumscribed areas for a certain time. It promises to become an important tool in establishing full causality in conjunction with complementing fMRI-studies.

Multi-electrode bundle recording is especially useful to broaden the scope of electrophysiological methods. The models that derive from those methods so far are single-neuron, cellular local models, which is maybe just an artifact of the method. Bundle-recording provides a chance to assess the activity of larger populations of neurons and the interactions between individual cells in their computational efforts.

As both of these methods are just in their beginnings, much can be expected from them in the near future.

In conclusion, this paragraph has become far larger than expected, but it pays off to focus on methods, as research in cognitive neuroscience is all about the methods and a deep understanding of the used methods can help in assessing the validity of the research on attention in cognitive neuroscience.

3.2. Effects of attention on cognitive processing

What happens in the central nervous system if someone "pays attention" to a stimulus vs. not attending to the same stimulus? In cognitive neuroscience, there is wide agreement and consensus about the following empirical effects:

On a cellular level: Modulation of response properties of the tuning curves of neurons

These results were obtained using electrophysiological methods. In general, neurons in all cortical areas that were examined yet, adjusted their firing rates in response to changes in the attentional status of the presented stimulus, including even areas as early in processing as V1 (Maunsell & McAdams, 2001). Also, the magnitude of attentional effects on the firing of neurons increases in "higher" cortical areas, for example from V1 to MT, from MT to MST (Treue & Maunsell, 1996).

The effects of attention on the response properties of the receptive fields of neurons have been quantified in a very precise way. The tuning curves of neurons seem to be affected by attention in a multiplicative modulation, a multiplicative scaling (Treue & Trujillo, 2000), which means that the amplitude and the peak of the tuning curve of the neuron increases, but not the width and shape of the tuning curve.

For example, the tuning curve of a neuron in MT is amplified by 10-20% in a multiplicative way, if a stimulus is attended vs. non-attended (Treue, 2001). This holds true, if the target stimulus is distinguished from the distracters by location. If target and distracter stimulus are distinguished by another feature (like direction of movement), the tuning curve is again amplified by 10-20% in a multiplicative fashion.

If a target is distinguished by location and another feature from the distracter, these effects are integrated in an additive way, modulating the tuning curve of the neuron by 20-40%. (Treue, 2001). The magnitude of attentional effects on the tuning curves of neurons are largest, if target and distracter are located in the same receptive field (Desimone & Duncan, 1995). If the attention is directed to the target in the receptive field that matches the stimulus preferences of the neuron, the neural response to the target stimulus is amplified by up to 100%, while the response to the distracter stimulus is suppressed.

If unattended, the stimuli in the same receptive field suppress the neural response of the neuron, mutually inhibiting each other. Attention to one of these stimuli inhibits this suppression effect, strongly amplifying the neural response to the target and strongly dampening the neural response to the distracter. (Reynoldts, et. al. 1999).

In conclusion, attentional effects could be measured very precisely on the level of individual neurons by electrophysiological methods and the findings suggest that attention indeed plays a crucial role in information processing on this level.

On the level of cell populations: Amplification, latency and synchronisation.

These results were obtained using psychophysiological methods. ERP-studies show that the processing of an attended stimulus vs. an unattended stimulus causes increased amplitudes and decreased latencies in the studied event-related potentials. (Hillyard, et. al. 1995). This effect seems to be stimulus-locked, exactly covariating with the deployment and withdrawal of attention on stimulus to stimulus level. These changes in the characteristics of the ERP most likely reflect enhanced and more elaborate processing of the attended stimulus. It´s not entirely clear, how the processing of the attended stimulus is enhanced on this level, but studies by Fries (Fries et. al., 2001) point out, that attention to a stimulus causes an increased synchrony of firing in the gamma-frequency-band of the EEG-signal while the synchrony in lower bands is decreases. This finding is very exciting, as increased synchrony in the gamma-band (over 30Hz) is generally associated with the binding of object-properties. Linking this common knowledge about binding empirically with attention is very exciting, and could probably serve as late support for Treismans theory of feature-integration. Another possible role of the increased synchrony in the gamma-band could be that it activates postsynaptic interneurons, which could inhibit the processing of distracters. But this is speculation. A more compelling finding about the processing of distracters is provided by Fu et. al. (Fu et. al., 2001). They point out, that the processing of stimuli can not only be enhanced, but also be suppressed by attention. The processing of distracter stimuli was found to be associated with increased synchrony in the Alpha-frequency-band of the EEG-signal (8-12Hz). This finding is also very exciting, as it can literally account for the filtering of unattended stimuli - high synchrony in the alpha-band of the EEG-signal is associated with an increase in noise in the signal to noise ratio of information processing, making computations hard to do. Also, this finding supports the potential role of the thalamus in attentional control. The synchronisation of Alpha-activity is done by inhibitory feedback-neurons in the thalamus, subserving thalamic gating.

Taken together, the findings in this section provide a coherent and inspiring picture about the effects of attention on neuronal columns.

On the level of cortical areas: General activation and base-line shifts

Most of these results were obtained using neuroimaging methods. It makes sense to distinguish between sites (the areas where attention effects the information processing) and sources (the areas that control and guide these attention effects in the sites). In general, the sources are believed to be more anterior, while the sites are more posterior (Posner & DiGirolamo, 1999).

One would predict that the sites are active in respect to the information processing tasks at hand (like visual areas in visual tasks vs. auditory areas in audition tasks), whereas the source areas should be invariantly active in guiding attention in the sites, independent of the specific tasks if the tasks involve attention, assuming that there is a dedicated circuitry that controls attention in the sites.

Neuroimaging studies show that there are in fact certain sites that are supposedly source-sites guiding attention, revealed by increased cortical activity in different attention-tasks. Converging results show that these are most likely parts of the prefrontal cortex (Gode Fockert, et. al., 2001) and the intraparietal sulcus (Rees & Lavie, 2001), suggesting distributed fronto-parietal networks of attentional control. (Downing et. al., 2001).

Also, there seem to be baseline shifts of activity in the sites. If the attention is directed to the target stimulus by cues, the subjects build non stimulus-locked baseline shifts of activity in the site areas that will process the stimulus, resulting in elevated baseline activity in these areas. Presumably, attention "prepares" these sites for the processing of the target, as these baseline-shifts take place in advance to the stimulus-onset itself. It´s very likely, that processing is facilitated, it target stimuli are processed in these prepared tonically modulated sites.

Unfortunately, these results were obtained by using different methods on different levels. It should be investigated if they correspond, deciding if they reflect the same effects on different levels of analysis or if attention affects these levels differently (see Braun, Koch & Itti 2001).

3.3. Models of attention in cognitive neuroscience

Again, many existing models couldn't be included because of limits in available space. Therefore, this section just contains some of the most prominent and exemplar models. The decision to chose those presented below among the abundance of possible others was a tough one. Hopefully, this choice was justified.

The biased competition model by Desimone & Duncan

The biased competition model of attention was initially developed by Desimone & Duncan (Desimone & Duncan, 1995) and enjoys wide theoretical and empirical support (Reynolds et. al., 1999; Reynolds & Desimone, 2001; Kastner & Ungerleider, 2001) in the field. It is based mainly on findings of cognitive neuroscience and therefore illustrates some interesting points about attentional models in cognitive neuroscience in general.

According to Desimone & Duncan, Attention solves a central computational problem: At any given moment, there is more information in the environment than can be used to enhance current behavior. Because of this abundance of input compared to limited output, behavior-relevant information always **competes** with irrelevant information for access over computational processing resources to influence behavior. Fortunately, in most cases, the irrelevant information differs from behavior-relevant information in several aspects. This allows attention to use this distinctive aspects to separate relevant information from behavior-irrelevant information in a winner-takes-all manner: Attention **biases** the **competition**, increasing the influence of behavior-relevant information in information processing and decreasing the influence of irrelevant information, allowing the organism to act in a more efficient way; like as if only the relevant information were present in the first place. Do differentiate things further, attention is conceived as top-down biasing of the competition. The competition can also be biased by bottom-up-influences inherent in the physical nature of the stimulus, implying that both influences are mediated and share the same neural architecture. So far the theoretical conceptions of this rather economical computational model.

What distinguishes the biased competition model of Desimone & Duncan from others is the fact, that they explicitly suggest a physiologically plausible neural basis that mediates this competition and mechanisms that allow for this competition.

Receptive fields lie at the heart of the neural basis of the biased competition model. As their model was conceived as a model for visual attention, it makes sense to exemplify the concept of receptive fields in the visual system: A receptive field in the visual system is the area on the retina, where a stimulation affects the response of the neuron in the visual cortex. In other words, a receptive field is the neuron´s window to the environment. It reacts only to stimuli in this window and is insensitive to stimulation in other areas. The author´s assume, that the competition between stimuli takes place if two stimuli share the same receptive field. This assumption is highly plausible, as receptive fields have many suitable properties that could account for many of the empirically obtained behavioral facts about capacity limited processing that have been obtained so far.

First of all, the number of neurons and receptive fields in the brain is limited, allowing it to be conceptualised as a resource in the first place. Moreover, receptive fields come in many different sizes, form very small (like in V1) to very large (like IT), differing in a factor of ca. 100.

If attention affects the receptive fields itself, it could actually resolve many theoretical worries, like the location and structure of the attentional bottleneck or filter.

The information-processing tissue itself would provide this filtering capabilities, without need for a structure that provides the filtering or selection.

In addition, the influence of attention in the information processing on the level of receptive fields would allow to reconcile even more conflicting empirical findings: Some studies show a “selection” for features, other for location, others for objects. As receptive fields have all kinds of response properties, this flexibility could be provided by the influence on receptive fields on different levels: Receptive fields early in processing allow a high spatial resolution and information about features, whereas receptive fields later in processing (like IT) are known to respond to whole objects.

These exciting characteristics of receptive fields are not the only ones that suggest their role in attentional influence on information processing: Attentional control on receptive fields is also more plausible than other potential resources, as attentional effects can be very subtle and concrete, influencing information processing by altering the response properties of the receptive fields of neurons is by far more direct, local and specific than would be possible by an influence on other resources like neurotransmitters or blood.

Last but not least, every single neuron with it´s receptive field can be conceptualized as a “filter” or funnel, integrating information from the whole receptive field into a single neural response (as every neuron only has one axon). The explanatory power of this notion is tremendous: It is not only possible to account for many emergent filtering phenomena by this underlying neural architecture – this concept also directly influences the early vs. late selection debate. Receptive fields are convergent, therefore their number decreases in higher processing areas, increasing the competition between stimuli in late processing. Attention could capitalise on that in a very flexible way, taking place wherever necessary to make information processing more effective. In this framework, every neuron and it´s receptive field sets up an own independent processing channel, allowing parallel processing of information, while the number of independent channels decreases in higher cortical areas. This idea is supported by the fact that attentional effects are indeed smallest in neurons in V1, where the receptive fields are of little size and presumably most channels are available, allowing for massive parallel early information processing.

Empirically, the biased-competition model is largely supported by electrophysiological studies in the ventral system. These studies assessed the modulatory effect of attention on neural response rates.

Attention has almost no effect in facilitating the neural response to an already salient stimulus. Salience is conceptualised as biasing the competition for processing bottom-up by fitting the selective response-criteria of neurons best. Another example of bottom-up influence on information processing is the “pop out” of highly contrasting stimuli due to lateral inhibiton. Attention can´t facilitate this pop-out much. The competition is already biased by bottom-up characteristics of the stimulus, favoring the processing of this stimulus. Moreover, attentional effects on neural response rates are generally small, if only one stimulus is present in the receptive field, enhancing the response by ca. 20%. If two unattended stimuli share the same unattended receptive field, these stimuli mutually suppress each other, the neural response is decreased, by averaging each other out.

If two stimuli share an attended receptive field, the attentional effect is largest, the response rate of neurons was found to be facilitated by up to 70% in favour of the attended stimulus, virtually cancelling out the effect of the non-attended stimulus (even if it better fits the selective stimulus preferences of the neuron). In most cases, the neural response under this conditions is almost indistinguishable from conditions in which only one stimulus is present, effectively eliminating the stimulus that lost the competition from further information processing. This characteristic is termed "winner-takes-all-algorithm" and could be highly useful in the regulation of information processing, restricting the access to higher processing areas to relevant stimuli by top-down processes that modulate the neural response characteristics of the information-processing "site"-areas itself.

The non-attended stimulus had so little effect on the response of the neuron if another, attended stimulus was in the same receptive field, that Desimone & Duncan conjectured a mechanism to account for this profound effect: They suggest that attention causes the receptive field to literally shrink around the target, leaving the distracter stimulus effectively outside the modified receptive field, rendering it incapable of influencing the response of the neuron.

Assuming the validity of this notions, Desimone & Duncan also suggest mechanisms that control and direct this flexible behavior of the neurons and the influence on the characteristics of their receptive fields.

They suggest that a description of the behaviorally relevant information is available in working memory. This description alters the response-properties of neurons and their receptive fields, controlling the competitive bias in a top-down fashion and favoring input that matches the description over input that doesn´t match it. Desimone & Duncan term this description of behaviorally relevant information in working memory "**attentional template**" which is presumably reflected in the pre-stimulus baseline-shifts of elevated tonic neural activity that were discussed above. Inputs with features that match those defined in the attentional template are therefore favored in processing because attention biases the competition (receptive field properties) towards the features that are pre-defined in the attentional template.

Summarizing, Desimone & Duncan (1995) conceptualise attention as a top-down bias on the response properties of receptive fields in neurons in site areas, controlled by attentional templates in working memory (source area). Therefore, the model takes the parallel and flexible processing capabilities of the cortical architecture into account, without a need to postulate additional serial scanners (like those implied in spotlight-models).

It´s appeal derives from the fact that it gives flesh to the fuzzy concept of processing resources and from the fact that it is specific enough to allow for empirically tests of the implications of the model on a neural level, as well as it´s integrative potential.

The feature similarity gain model by Treue & Martinez

This model also bases on electrophysiological data and was developed by Treue & Martinez (Treue & Martinez, 1999; Treue, 2001) using data obtained in the MT and MST of the macaque. It was proposed as an alternative to the biased competition model to account for some data that is in disagreement with predictions derived from the biased competition model.

Interestingly, their model shares many conceptual ideas with the biased competition model and also confirms most of the empirical findings – with some important differences.

The model also conceptualises attention as a top-down mechanism regulating information processing in order to focus on behaviorally relevant information. They emphasise the constructive role of attention in transforming the isomorphic representation of physical stimulus characteristics in early processing areas into a goal-related perception of the world in later processing.

Empirically, they confirm the finding that the effect of attention can be measured in terms of modulated neural reponse rates and that the effect is larger in higher processing areas.

They also share the notion that top-down influences by attention and bottom-up influences by the physical characteristics of the stimulus affect the same processing structures, as attentional effects only influence the **gain** of neural responses; the modulatory effects on response rates for given stimuli are only multiplicative, without change the shape of the tuning curves of the neurons. This implies that attention merely changes the salience of the physical stimulus for the organism, not changing or biasing the selective sensitivity of the receptive field itself, which means that the same effect in terms of neural firing rates resulting from attention can be achieved and mimicked by increasing the physical intensity of the features of the stimulus – the tuning curves are neither skewed by attention, nor do they change width.

Therefore, there is little disagreement over the basic notions and effects that were put forward by the proponents of the biased competition model.

Treue & Martinez do disagree over the mechanisms, by which these effects are brought into existence. According to them, a shrinking of the receptive field around the target is highly unlikely: In some of their experiments, they superimposed random dot patterns moving in opposite directions, where the animal was training to pay attention to one movement-direction of the patterns. The modulatory effects of attention on the tuning curves of the neurons persisted; however, as the dot-patterns were totally superimposed in spatial terms, it´s impossible that a spatial reorganisation of the receptive field can account for this effect. The authors propose a general reorganisation in terms of stimulus-features (with unknown underlying mechanisms). Moreover, if an animal was trained to direct attention to a certain stimulus feature (like direction of movement), they found gain effects of attention to this feature throughout the visual field, not limited to certain receptive fields, disputing that receptive fields are the crucial processing resources in an assumed competition as proposed by Desimone & Duncan. This finding is supported by the complementary finding that the neural response to unattended features is suppressed throughout the visual field.

Generally, they doubt that attention enhances the influence of attended target stimuli on the expense of unattended distracters in a hypothetical competition; alternatively, Treue & Martinez conjecture, that attention modulates the overall responsiveness of a neuron (in accord with the found modulatory scaling) based on the relation between the neuron´s preferred and attended stimulus **features** to explain the empirically found effects.

In conclusion, this model proposes an interesting theoretical alternative to the biased competition model, pointing out that even seemingly compelling empirical evidence doesn´t rule out an – in principle – infinite set of possible theories that could explain the empirical findings. Of course, further empirical evidence is necessary to decide between these two (and other) possibilities.

LaBerge´s structural model

While the previous two models try to make sense of the attentional effects found in "sites", this model deals with the potential sources of attentional control, illustrating another type of attentional models in cognitive neuroscience: Structural models.

The latest model by Laberge (1999) is of particular interest, as it sincerely tries to integrate as much empirical findings and earlier models (like the thalamic spotlight model by Crick & Koch) as possible.

As virtually all structural models, it´s based on neuropsychological findings and data from neuroimaging studies. It doesn´t really pay off to go into detail here, as most structural models can´t cite too much undisputed evidence in favor of their position and are always entailing many unwarranted assumptions as well as often relying on plausibility arguments derived from neuroanatomy.

Briefly, Laberge conjectures, that at least three brain regions are concurrently involved in the control of attention: Frontal areas, especially the prefrontalcortex; thalamic nuclei, especially the Pulvinar and posterior sites, especially the posterior parietal cortex and the interparietal sulcus. Laberge proposes that these regions are necessary for attention as they mediate the large-scale amplification of neural activity, something that presumably can´t be done by the affected regions itself or other regions like the brainstem, due to a lack in selectivity of neural connectivity.

As these regions presumably give rise to attentional control together, little is known about their differential functional role. Laberge proposes that the frontal areas give the amplification commands which are mediated by circuits in the thalamus and that these distributed regions are interconnected in a triangular attentional circuit.

Again, I don´t want to go into detail here. The main reason why I discussed the model in the first place is, that it (like many others) neatly illustrates our very coarse and premature knowledge in the understanding of attentional control by source sites.

So far, we can only conclude that we have these (and many more) models, that they came into existence through research in cognitive neuroscience and that they can better account for empirical data than most of the models before. But we can´t yet really differentially evaluate and assess the validity of these models. They all derive from different sets of data and findings and all emphasise different processes. They are not necessarily mutually exclusive. But one would need specially designed studies to differentiate between them. It´s too bad that scientists tend to be biased to look for confirmatory support of their theories rather than for strong empirical tests.

Treue´s model seems to be valid in MT and the dorsal stream, while the findings of Desimone and Duncan can´t be disputed in the ventral stream. Moreover, the structural source models are mainly derived from neuropsychological and neuroimaging methods while the two mechanistic processing models are based on findings obtained by using electrophysiological methods. It´s just premature trying to judge them relatively to each other. The existing body of appropriate data is insufficiently sparse to date.

3.4. New approaches to resolve old questions

This paragraph reviews progress in attempts to answer some of the open questions in attentional research that were discussed in section 2.2., adding evidence from the perspective of neuroscientifical approaches in this paragraph.

The nature of resources: Even if not undisputed, the approach by Desimone & Duncan (1995) is the most compelling at hand. The proposal of receptive fields as the sites of competition for limited attentional capacities (resources) is in accord with most empirical findings and allows specific predictions on the influence of attention on information-processing, which provides a solid and fertile basis for future research. However, this doesn´t rule out the possible existence and potential relevance of limited attentional resources on other cortical levels and interaction-effects with other, more coarse resources like blood or neurotransmitters that could indirectly modulate the effect of attention on receptive fields and information processing if made necessary by computational demands.

Mechanisms and nature of attention: In general, the conceptual distinction between sources of attentional control and sites which execute the attentional control in terms of a modulation in neural firing rates seems to be reasonable and useful. Noticeably, attentional effects on neural response rates have been found in every cortical area yet examined, including V1. This supports the idea that in terms of the sites, attentional modulation is a general property of neurons. It´s a flexible degree of freedom that allows to regulate and optimize information processing in relation to processing goals on a neural level, which is presumably highly evolutionary adaptive for organisms with sophisticated sensory capabilities to extract much information from a complex and rich environment of physical stimuli. This attentional system is obviously very flexible, can enhance the neural response rates to attended stimuli as well as suppress the neural response rates to unattended stimuli, giving effectively rise to both phenomena: Selection and filtering.

In terms of attentional control and sources, the status in research is unsatisfying. Some argue for a unique system of areas that is always active in all kinds of attentional control (Laberge, 1999), others like Nobre (2001) point out, that attentional control is actually dependent on the specific attentional task, citing evidence that directing attention towards temporal locations engages different cortical source regions than directing attention towards spatial locations; especially the intraparietal sulcus is presumably only active in tasks of spatial attention, disputing the notion of a single unified attentional mechanism.

Some even claim that specially dedicated cortical circuits for the control of attention are not even necessary, but the site areas are enough on their own in a self-organisatory manner (with the evidence in favour of source areas merely reflecting task-demands).

Early vs. late selection: The concepts involved in this question most probably don´t map on a neural level: In temporal terms, attentional effects can be observerd as early as it gets: Some occur even before stimulus onset, stimulus-locked differential effects can be observed before the N100 (Hillyard et. al. 1999). In terms of processing areas, all cortex tissue seems to be subject to attentional control, even V1. With this in mind, there is also evidence that attentional effects accompany the whole cognitive processing of a stimuli, kicking in whenever needed to achieve computational goals, becoming more influential in later cognitive processing. There is even support for selection on the sole basis of objects (Blaser et. al., 2001). But it´s maybe really most accurate to conclude that attention takes place on virtually all levels of information processing, reflecting the highly flexible nature of attentional control itself (Posner et.al., 1999), using the spatial resolution provided by V1 if necessary or capitalising on identified object properties in IT if needed.

Automatic processing and the fate of unattended stimuli: ERP-studies (Hillyard et. al., 1999) and neuroimaging studies clearly show that attention is not necessary to process stimuli up to a very high level of cognitive information processing. If salient enough, these are even capable of overriding attentional control becoming aware (oddballs). However, the same studies also show that the processing of these stimuli is somehow different from attentional processing – reflected by decreased amplitudes and increases latencies in ERP-studies and decreased cortical activity in neuroimaging studies.

Selection for features, objects, or locations? Again, definitive conclusions are premature, but everything has been claimed by different authors: Locations (exemplified by Desimone & Duncan, 1995), Features (see Treue, 2001) and also objects (Blaser et. al., 2001). Most likely, the systems that control attention are flexible enough to make use of whatever characteristics distinguish between targets and distracters in the flow of incoming information. As all authors propose compelling evidence for their notions and these possibilities are not mutually exclusive, the idea that the attentional system has this flexibility is the most sensible position to take, until future evidence proves otherwise.

Filter vs. spotlight? As pointed out above, attention can mimic characteristics of both. However, Treue (2001) makes plausible that at least the notion of attention as a spatial spotlight is invalid. Apart from the fact that receptive fields in higher cortical areas don´t provide the spatial resolution needed to allocate attentional resources in the ways that obviously take place in the cognitive system, this notion is also incapable of accounting for some other effects (like differentially enhancing spatially superimposed stimuli). If one wants hold on to the spotlight-metaphor, it´s more accurate to conceive attention as a spotlight that operates in a complex n-dimensional spatio-temporal-feature space.

An alternative interpretation of the existing data is that the spotlight is defined in dimensions in which the modulated neurons are tuned, allowing the receptive fields in IT and V4 to shrink around the target due to attention, but requiring spatio-temporal reorganisations in MT.

Relations to other functions: Not too much research has been done yet to clarify this question. However, attentional source control seems to be intimately tied to (if not identical to) working memory (Gode Fockert et. al., 2001).

In conclusion: Considering the difficult nature of these questions, considerable progress has been made. Many effects have been shown. Some of them seem to be mutually exclusive, given the assumptions of the concepts that predicted them. But actually, showing that an effect occurs in a certain experimental paradigm logically doesn´t rule out, that it can´t possibly occur in another one; this naïve research strategy led to an inflation of findings and conflicting concepts.

The most probable conclusion so far: It´s unlikely to be able to integrate all the contrary findings in one unifying conceptual framework of attention, because there is simply no unified mechanism underlying them, but rather several ones, operating on different levels and with different computational constraints, serving different goals, resolving the seeming paradox.

However, differentiations like the site/source distinction prove to make sense in this context and show the power of cognitive neuroscience; clearly, it has the potential to refine our concepts given the current status of our research.

3.5. Remaining challenges

As pointed out in earlier sections, cognitive neuroscience has become dominant in attentional research and was actually able to come up with preliminary evidence relevant for many questions that were unresolved before. However, it has to be crystal-clear, that all that has been done so far can only be considered as a reasonable start – with most of the work is still ahead of us. This section will try to point out some of the most important challenges that have to be overcome by the cognitive neuroscience of attention if they don´t want to suffer the same fate as their predecessors in cognitive psychology before them.

One of the most salient characteristics of the cognitive neuroscience of attention is it´s limited focus: While the study of attention in cognitive psychology started in the modality of audition, it was almost entirely restricted to the modality of vision in cognitive neuroscience. It remains largely unclear, if the conclusions obtained in vision can be generalised to other modalities. More research in more modalities is needed to make sound generalisations. This could also be relevant for the question if there are common invariant attentional mechanisms or if they are tied to the respective task and modality.

In a similar fashion, there is a methodological gap yet. As pointed out in section 3.1., for example, most methods apply to humans, but the compelling electrophysiological evidence is based on research in non-human primates. We don´t really know, if the results of these different methods really map onto each other. This is especially crucial, as electrophysiological methods have – in principle – the potential to uncover the mechanisms of attentional control and mechanism of attentional mechanisms. So far, we have a crude understanding of the effects of attentional control, but no real understanding of how they come into existence.

Most recent findings (Blaser et. al. 2001, Braun 2001) that used paradigms involving superimposed rapidly morphing objects and the remarkable ability of subjects to attentionally track these objects reflects that our existing concepts of object recognition are premature at best. As Blaser et. al. point out, we need to conceive better theories of object recognition and more linking hypotheses to attention if we want to make sense of these most challenging findings in attentional terms.

As useful as the distinction between sites and sources of attention is – it raises the question about the relationship between those. While some boldly advance their models like Laberge (1999), others contest if source sites are even necessary for attentional control. Undisputably, the neural activity in the sites is generally flexible – neurons are capable of flexibly adapting their tuning properties to current processing requirements. Presumably, the sources guide this process, synchronise and direct it. While the remarkable ability of a cybernetic, biochemical information-processing system to dynamically tune itself to enhance the quality of processing in respect to certain stimuli and certain goals is not disputable in the sites, the existence of source-systems is largely a matter of assumptions and logical reasoning:

Some assert that the site-systems need true "top-down" control to organise and synchronise the coordinated simultaneous modulation of the tuning properties of many neurons. If they tune for different things in an uncoordinated way, this would presumably be not of much use. This logic implies the need for higher control centres. But it could well be, that this logic is not valid after all. On the one hand, this logic leads to an infinite regress: Who tells the frontal areas, what to do? How do they know? This is effectively the search for the homunculus in the brain. The futility of this kind of reasoning has been shown many times. On the other hand, the physics of complexity theory has shown the obvious power of self-organisation and self-organising systems. (Haken, 1993). It´s entirely possible, that there is no need for "top-down" control beyond a very local and hard-wired level. It could pay off to look for dynamic linking between neurons to show that they effectively form a self-organising system, providing the effects of attention all by themselves, abiding to the laws of complexity theory.

Then again: How to explain the elevated activity in inferior parietal sulcus and baseline shifts? These don´t necessarily reflect attentional control. The activity in the inferior parietal sulcus could be a prerequisite for concious awareness of attentional effect or reflect some other activity like eye-movement control. The studies that tried to show the “invariance” of this activity despite different task demands were not so systematic after all. Most of the used similar paradigms. This activity could well reflect task demands. The encountered baseline-shifts were obtained by repeated cueing and can be attributed to all kinds of effects: Priming, Expectations, mental imagery, etc., and don´t necessarily need “attention” as an explanatory construct. These alternative explanations have to be carefully ruled out in a systematic manner before the claim of the existence of distributed source systems is compelling.

On the basis of our knowledge so far, both possibilities remain: Either attentional effects reflect the working of a distributed attention-controlling fronto-parietal circuit, the “source”-system that guides attention in temporal-occipital “sites”, modulating the information-processing there in accordance to higher processing goals, or the possibility, that there is no need for a source-system, and neurons in general have the meta-property of flexible tuning properties, leading to these effects that we label “attention” on an emergent, molar level.

Also, cognitive neuroscience should undertake the most rigorous attempts to finally explore the relationship between attention and other cognitive functions. Very little is known about these so far. For example, as most would assert that attention serves an important role in goal-related information processing subserving goal-related behavior because of it´s evolutionary adaptiveness, this a mere just-so story. In fact, the potential relationships between attention and motivation are unquestionably very interesting, but remain largely unexplored so far. If attention itself survives as coherent field in this quest to relate it to other fields is not clear. As there are most likely “attentional” effects to be found everywhere in the brain, which are probably **not** subserved by a single “attentional” system, it´s not absurd to posit that the study of attention could be dissolved in the study of the flexible tuning capabilities of specialised systems like perception, action or memory. It´s no resolution to formally conceptualize attention as general, flexible selective modulation capabilities of the neural properties of the nervous system in order to improve goal-related information processing. The problem with this conception is that it´s not very exclusive in respect to other concepts. All kinds of extraretinal influences have a modulatory effect on neural firing, including arousal (mainly subserved by the formatio reticularis (ARAS) in the brainstem), eye position and imagery. If could be very tough to conceptually separate those without losing a coherent body of effects that can be termed “attention”.

Finally, in a more general perspective of challenges, the introduction of new methods has the potential to uncover many interesting empirical results and neural mechanisms of behavioral phenomena. On the downside, it spawns the risk of bringing up even more conflicting findings than before, overwhelming researchers by the complexity of the brain at a neural level; many effects are known now, but it´s still unclear how they work or how we can explain them yet or if we will ever be able to explain them. This is tied to the fact that we should not lose track of all the theoretical problems that seem to be inherent in the concept of attention. Maybe the psychological questions and concepts principally don´t map onto the neuroscientific findings that are mostly defined in different terms and very sensitive to specific operationalisations.

4 Discussion, Summary and Conclusion

Of course, this brief paper couldn´t discuss many of the issues that are currently en vogue in the cognitive neuroscience of attention like the relation between attention and working memory or the frontal control of attention in a more detailed manner. Some issues weren´t touched at all. Yet, I think I have outlined some of the principle problems that will continue to accompany further research of attention in cognitive neuroscience in the future. It remains doubtful if cognitive neuroscience can easily bring the salvation to the study of attention that so many have hoped for.

Much is to clarify on theoretical, conceptual levels. This clarification necessarily has to precede or at least accompany the interdisciplinary study of attention and attentional effects with new methods within cognitive neuroscience; yet, not many theoretical issues could be definitely resolved by the use of this fancy methods like neuroimaging, electrophysiology or the like so far.

Moreover, one can hardly avoid the impression that the devoted theoretical grounding of studies and research has been widely abandoned in cognitive neuroscience and the use of sophisticated technical equipment theoretical was done on the expense of rigorous theoretical reasoning. Many crucial and nagging theoretical problems seem to be totally neglected by cognitive neuroscience and remain a constant source of grief. As all research is ultimately done to resolve theoretical question and results only make sense if interpreted in a certain theoretical framework, this unnecessarily limited the yield of using methods of cognitive neuroscience in the past.

Therefore, the dissociation between the theoretical white-box models of cognitive science and the rigorous use of technical methods pretending to do untheoretical, strictly empirical research in cognitive neuroscience largely still remains in attentional research (revealing the naïve positivist positions of many researchers in the field). Yet, clearly the potential is there for a mapping of these levels onto each other. Especially the troubled and important field of attentional research could use this unity to resolve some of the basic problems in the field as well as providing an inspiring example for the whole of psychology and cognitive neuroscience.

Nevertheless, the findings so far are encouraging. With more consideration of neglected theoretical issues, there is indeed much more cross-fertilization between physiological methods and psychological concepts to expect from this strain of research in the future.

What do I mean by neglected theoretical issues? I want to discuss one of the major cases in broader detail to illustrate my point:

The direction of attention: Even though this issue is a central and critical point in Pashler (1999), surprisingly none of the empirical papers I read explicitly addressed this issue or recognised it as a particular problem, even though some of them referenced him. The problem of the direction of attention wasn´t only critical for cognitive psychology (which invented all kinds of manipulation checks like shadowing to assess the direction of attention), it remains critical in cognitive neuroscience.

Why is the direction of attention a critical issue? As pointed out earlier, attention remains the big theoretical joker even of neuroscientists, used to explain all kinds of effects that can´t be accounted for easier or otherwise.

As “attention” is not as easily observable or clearly definable as other fields of cognitive psychology like perception, action or even memory, the concrete operationalisation of “attention” or the direction of attention in the respective study is particularly crucial.

There are multiple ways reported in literature, how attention was supposedly directed. These ways don´t necessarily map onto each other, don´t necessarily tap the same phenomenon and don´t necessarily have to be accounted for by invoking the concept of “attention” at all, in most cases there are alternative possibilities.

At least 6 different ways to direct attention are commonly reported in the literature:

Explicit direction: The trivial way. Subjects are simply and explicity asked or instructed to "pay attention" to a certain object, feature, location or channel. This method is as convenient, as it is stunning: If the researcher has no clear idea, what attention is, how are the subjects supposed to do it? Who knows, what they are doing or if they are all doing the same. There are a lot of hidden assumptions, like that the subject is voluntary able to do so and that this process is in fact attention. Summed up, this approach is questionsable - for a lot of different reasons, maybe it has the potential to uncover the neural underpinnings of the everyday understandings of attention as used by the subject – it they all share the same understanding.

Task demands: Attention isn´t directly mentioned in the instructions. The subject is just instructed to do the task itself. These tasks are typically designed in a way that the subjects either have to fixate a point or the stimuli presentations are too short for saccades, ruling out the possible interference from eye movements. In an exemplar study, subjects compare different pairs of stimuli or search for a particular stimuli in a larger set. As the stimulus situation is the same for all subjects, differential effects in the dependent variable are attributed to attention, and the results interpreted as reflecting the nature of attention. With different task demands and instructions, all kinds of different effects and mechanisms could underlie the performance. Not necessarily attention-related…

Cueing: Became extremely common recently. Subjects are commonly cued to a certain location in space or time. As eye movements are ruled out as explanations, all differential effects are attributed to reflect attentional effects. The cues establish expectations in the subjects.

Attentional tracking: Also used occasionally. Subject are asked to track one or more objects with attention without eye-movements, while some of the properties of the object(s) change and the subject is asked to report these changes.

Training: Common in animal studies. Animals are trained to differentially respond to (rewarded) target stimuli vs. distracter stimuli while keeping eye fixation on a fixation cross. The fact that animals are able to do so and target vs. distracter stimuli elicit different neuronal responses is attributed to the existence and functioning of attention.

Not reported: This is also especially nice. Some studies don´t even report in the article, how the direction of attention was achieved or operationalised. They simply report "attention was directed to xy". That´s it. Amazing enough that the article passed the reviewer, but this also reflects that this part of the study is not always seen as crucial.

Most of these methods were already used in cognitive psychology, but the need for sophisticated manipulation checks was widely acknowledged; recently, even this basic caution is often lacking. Besides, the role of eye-movements remains unclear. In most studies, they are ruled out by fixation-training or short stimulus presentations, in some studies they are allowed. In some studies eye-fixation is important to keep the object on the same place on the retina, which means on the same receptive field (like in electrophysiology), others find it important to rule out eye movements to rule out interaction effects and study "pure" attention. Interestingly, many studies let subjects fixate the eyes and find no serial effects. Maybe the notion of a serial scanning spotlight that was proposed by some theorists actually reflects the programming of visual saccades in everyday life. Clearly, this is also a qualitatively different type of attention, but has definitely spotlight-characteristics due to the distribution of receptors on the retina and is ecologically valid, as people shift attention in accordance with eye-movements in most natural situations. Maybe the fixation-requirements introduce a methodological artefact that is not ecologically valid at all and needs to be overcome in the long run, as soon as the effects that can be obtained without moving the eyes are established. This is speculation, but should be studied in a more systematic manner to potentially resolve some of this conflicting claims in the future.

Why is this state of affairs a mess and poses a theoretical, conceptual problem that threatens the validity of interpretations of empirical findings in attentional terms in general?

Because the observed effects are attributed to attention in a manner of backward reasoning: If effects are found and can´t be easily explained otherwise, the effect of attention is inferred.

Moreover, I´m not convinced that the many different operationalisations of attention all tap the same underlying phenomena that could be termed attention. Most likely, the subject-matter of different studies is not identical, rendering all speculations about the differences between findings on empirical grounds as senseless and seriously disturbed, merely reflecting the hidden conceptual problems, brought to the empirical level by a flawed operationalisation – the differences in the findings could be potentially incommensurate due to this fact.

All kinds of different theoretical constructs could hide behind the different operationalisations outlined above: Priming effects, expectations, motivation, specific task demands, spatial primacy effects, spatial working memory, motor intentions and many more. Obviously, the effects can intrepreted in other frameworks besides attention. It´s just a conceptual chaos and a theorists nightmare.

Also, the theoretical debate, if attention selects for objects, features or locations could largely derive from the fact that the respective studies arguing for the one or the other are in fact mainly and exclusively using different operationalisations, (task demands, cueing and attentional tracking, respective) not from the nature of attention itself.

This is not to be taken lightly, as it threatens the validity of the research in the whole field. The implications of the different operationalisations are just unclear. Either there need to be studies done that explicitly show that all these operational methods to elicit and direct attention are in fact valid and identical effects on the empirical level, showing the commensurability on an empirical level or agreeing on a valid method to operationalise it, abolishing the others. This would also be very nice, as it would operationally define attention - without an agreement on a theoretical level, this is the least that is required for the sensible scientific study of any phenomenon (and still lacking in attentional research). Else, all empirical findings can´t possibly be expected to match with each other because they don't even tap the same phenomenon; without this step, the study of attention is ultimately essentially futile and unlikely to be able to progress much - despite all technical wizardry - because of this hidden conceptual obstacles and theoretical shortcomings.

The integrity of the whole field is at stake with this issue – nothing less. By pointing this out in the most explicit and drastic manner, we retain the chance to overcome these conceptual challenges. This could indeed open up a more positive outlook towards the future of attention in psychology and cognitive neuroscience.

The potential is there: So far, research in cognitive neuroscience was able to come up with exciting and promising findings, taken into account that the most prominent methods are not in use for more than 10-15 years.

Also, one should face it: The merely cognitive study of attention has come to an end. Pashlers book can be interpreted as an attempt to deconstruct the whole phenomenon in a Wittgensteinian manner, which can in turn be interpreted as an announcement of "surrender" – obviously cognitive psychology has reached the ceiling of what can be achieved by relying on strictly behavioral reponse measures in an asymptotic manner.

Yet, either due to conceptual shortcomings, or due to the complex nature of attentional processing in the brain itself, cognitive neuroscience still adds to the complexity of the field, without actually resolving much of the issues or regaining the coherence of the field that was lost for so long, which reflects our still premature understanding of the phenomena at hand.

The future will certainly show if we can overcome theoretical problems and reveal the nature of attention.

Altogether, we should also appreciate that the study of attention has gone a long way, far exceeding the notions of everyday notions about attention, even without consensus over basic questions. Maybe this actually reveals the elusive nature of attentional phenomena itself.

The only real agreement that I found in the literature (outlined in the most "introduction" sections of the articles) is over the notion of the general function of attention as a means to enhance the adaptivity of behavior in a world of complex stimuli by modulating the incoming sensory information in accordance with goal-related behavior, facilitating goal-relevant information (which is a just so story); there is much less agreement over anything else.

With this outlook on the future in mind, let´s briefly focus on the current situation again, to remind us one essential question: Was it worthwhile? Do we know essentially more about the nature of attention with cognitive neuroscience than without?

Let´s be fair: After all, we shouldn´t discard the apparent progress that has been made. A good example is our new knowledge about the modulatory effects of attention on the tuning-curves of response-properties of receptive fields in single neurons. Before cognitive neuroscience, we knew nothing about that at all, now we can precisely quantify the effects. On the other hand, this exemplifies the continuation of another trend in attentional research: We have another empirical effect, presumably caused by attention and we have no good or conclusive explanations about **how** it works, what mechanisms underlie it or what precisely **causes** this effect.

Altogether, out notions about attention have come a long way, which is not too bad. They have gone far over and beyond everyday intuition. The fact that there is no real consensus over basic questions. could really reflect the elusive and complex nature of the phenomena at hand.

Cognitive neuroscience has certainly transformed the field and how we view attentional problems. The advantage is, that we have access to processes that are actually going on in the brain in terms of activation and electrical activity and don´t rely on coarse metaphors or biased analogies. If this helps to enlighten us over the question what attention really is and if it was worthwhile to use methods of cognitive neuroscience is still disputable. Yet, the preference of one of these viewpoints over the other is more a matter of taste and personality. It´s premature to draw a definite conclusion based on the data at hand. Certainly, we know a lot more and have gone far beyond the crude mechanical models like those that were around just 50 years ago.

If it´s possible to resolve conceptual issues like the matter of directing attention, this could lead to a real breakthrough in the field of attention – so far, innovation by cognitive neuroscience came through the introduction of new methods. It´s not too oversimplified to assert that cognitive neuroscience vastly expanded our capabilities to measure dependent variables. We obtained radical new methods to precisely measure subtle effects in these dependent variables, like neural firing rates. On the other hand, the development in terms of independent variables lagged behind. We don´t do much more or different on the level of independent variables than we did before cognitive neuroscience. This is a deficit that needs to be dealt with. The introduction of the new TMS-method is a start. If this trend joins forces with good conceptual grounding, the prospects are indeed promising even if it´s still not clear if attention will survive as a coherent field itself in the progress – it could as well be possible that attentional research is dissolved in the specialised study of more clearly defined domains like memory, perception, etc, as attentional effects can be maybe be fully interpreted and understood as disjunct aspects and properties of these processing systems.

In conclusion:

Given the special problems commonly encountered in attention research, this branch of psychology could particularly benefit from a joint-forces approach with cognitive neuroscience. In my view, attention research has the potential of becoming one of the most intriguing and relevant fields of psychology in general, if this approach works out. On the other hand, the risk that the field could end up as the worst mess in all of psychology and the possibility that the field might even become abolished remains. It´s unclear, how this will turn out. So far, the research of attention is a challenge for psychology and cognitive neuroscience as well as still the problem child of these fields.

It´s no wonder that the behaviorists sidestepped it in the good old days… ;)

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