Chapter 1

Levels of binding: types, mechanisms, and functions of binding in remembering

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Introduction

When considering binding one might first think of perception and not memory, because the problem of binding is most frequently discussed at lower perceptual processing levels in which elementary stimulus features are encoded (Kanwisher and Driver 1992). If it is assumed that different features are separately represented in a distributed neural structure, a problem arises if more than one object is in view, namely, how to represent the fact that a set of specific features belongs to object A, and others, although active at the same time, belong to object B (Treisman 1996). This problem of analysing and representing relations among features is not restricted to perception, but is a general problem of cognitive processing. In thinking, remembering, and knowledge representation, features are processed within distributed systems as sets of separate units in a highly parallel way. As a consequence, elements belonging to the same cognitive 'event' have to be bound and separated from other features belonging to a different 'event'. Similarly, during enactment, binding is necessary in the form of attachment of task-relevant features to the intended action (see Chapter 13). Finally, memories are traces of processes performed during encoding, and therefore binding mechanisms strongly specify the input to memory. Moreover, binding may even be highly relevant for consolidation of distinctive memory traces and for retrieval because features have to be re-bound at the time of remembering (Nader 2003). Hence, the binding problem is a ubiquitous one that has to be solved in perception and in action; it is also a problem in memory because binding of features is necessary during encoding, consolidation, and retrieval.

Therefore we consider binding mechanisms to be basic operations of cognitive systems, performing different functions at various processing levels, with their

efficiencies being a limiting factor for a number of mental processes. If this is correct, factors that either enhance or impair the efficacy of binding may explain much of the variance in performance between different situations, between different individuals, and over the lifespan. Therefore changes in binding processes may explain changes in a wide range of behaviour, and knowing how the neural system enables binding at various levels would enable us to closely relate cognitive performances to neural mechanisms. Hence, in our view, an adequate conception of binding is a cornerstone of a neurocognitive model of memory. This book should contribute to the grounding of such a model.

A selective view of the history of binding

Assuming that memory entries are made up of bound features is not a new idea. In many theories, memory entries are treated as sets of attributes which must be grouped in some way in order to constitute distinctive episodes. An early example is the suggestion of associative memory (Underwood 1969); other examples are formal models of memory, such as the search of associative memory (SAM) model (Raaijmakers and Shiffrin 1980) and the various types of 'vector' models (e.g. the theory of distributed associative memory (TODAM) (Murdock 1993)) which represent an event as a vector of features.

Similarly, the idea of conjoining attributes to units is not new in memory research (Ceraso 1985). For instance, the concept of 'chunking' (Miller 1956) refers to a binding effect. Entities are grouped by some mechanism to form larger entities, which can be used as units in further processing (if binding is successful). Grouping also has an important role in SAM theory (Raaijmakers and Shiffrin 1980); units are formed by association of concepts in working memory, and they strongly influence retrieval. Similarly, the problem of binding is explicitly addressed in vector models (Humphreys et al. 1994). Empirically, binding in mental processes has been investigated in a number of different experimental paradigms. Garner's research on integrated and separable dimensions is a good example of the investigation of binding in perception (e.g. Garner 1974). The work of Asch et al. (1960) on memory for unitary versus separate stimuli and the work of Jones (1976) on feature binding in memory retrieval are examples of behavioural studies on binding in memory. The best known research is probably that on feature integration (Treisman and Gelade 1980); for a summary and an extension, see Chapter 12.

Obviously, considering memory entries not as holistic units but as sets of separate features is a relatively common assumption in psychology, and as a consequence some kind of binding mechanism must often be assumed. What is new in recent research is the attempt to search for neurophysiological correlates of these mechanisms and to disclose binding processes at the neural level. When

representing entities in distributed neural nets, one has to solve the problem of indicating which elements belong to each other. Since the 1980s this topic has been explicitly addressed in neuropsychological and computational models as 'the binding problem' (e.g. Damasio 1989).

Several suggestions as to how the brain solves this problem have been made (e.g. von der Malsburg 1995). The most popular explanation currently is **temporal synchronization** of the discharges of individual and feature-specific neurons which form dynamic cell assemblies (Singer *et al.* 1997). Synchronization within cell assemblies was first used to model the perception of objects (Hummel and Biederman 1992), and physiological evidence for the synchronization of oscillating neural patterns has been reported for both animals (Engel *et al.* 1991, 1992) and humans (reviewed by Tallon-Baudry and Bertrand 1999). Synchronization has also been suggested as a mechanism for other kinds of binding, including task sets in actions (von Stein *et al.* 2000), binding before and during voluntary movements (Tallon-Baudry and Bertrand 1999), and binding in memory, as discussed in several contributions to this book (e.g. Chapter 9). Dynamic binding by synchronized cell assemblies may even play an important role in consciousness (Singer 2001).

Whereas with synchronization a fundamental mechanism for binding is in focus, other equally important aspects concern the neural structures that mediate binding and their relations with different types of binding. From this perspective, it is of interest to establish whether qualitatively different forms of binding exist, and whether they are provided by different neural structures. For example, it has been proposed that the frequency of the oscillatory patterns in which synchronization is observed decreases as one proceeds from low to higher processing levels (Singer *et al.* 1997). It follows that injuries to specific brain structures should lead to impairments in performing specific tasks, depending upon the forms of binding that are affected. From the viewpoint of memory, an interesting distinction in this respect is that between **recollection** and **familiarity** in remembering (reviewed by Yonelinas 2002), and their neural implementation. The importance of these processes for the understanding of remembering is reflected by the fact that this distinction is a central topic of many chapters in this book.

As early as 1980, Mandler had suggested that recognition can be based on either a feeling of familiarity, caused by integration of item-specific information without any context association, or recollection, which includes retrieving the context of an item, giving the individual a strong impression of when and where it was previously encountered. Stimulated by this proposal, several experimental paradigms were suggested to distinguish these subcomponents of recognition memory. According to Tulving (1985) and Gardiner (reviewed by Gardiner and

Richardson-Klavehn 2000), different types of subjective awareness are associated with both types of recognition, i.e. **remembering** and **knowing**. Because this classification is based on self-reports in recognition memory tasks, it is called the first-person view of memory. Subjects label a memory 'remembered' when they consciously retrieve specific contextual details of a study episode, and 'known' when they feel familiar with the event but are not able to retrieve any contextual details of its prior occurrence. Because the remember–know procedure is easy to use, it has become quite popular in experimental memory research. Another procedure is estimating familiarity and recollection from **receiver operating characteristics** (ROC), sometimes called memory operating curves, which are constructed by plotting memory performance as a function of response confidence that participants assign to their recognition judgements (Yonelinas 1994; see also Chapter 17).

Jacoby (1991) had less confidence in individuals' introspective abilities. He developed the **process-dissociation procedure** for estimating the contribution of familiarity (automatic retrieval) and recollection. Participants study two lists and are then assigned to one of two test conditions. In the inclusion condition, they have to accept all old items and reject new ones. In the exclusion condition, they have to discriminate between lists and accept only items from one list, while rejecting those from the second list together with new items. In the inclusion condition, familiarity and recollection work in concert. In the exclusion condition, particularly when considering the items from the to-be-rejected list, the two processes work in opposition. Performance in both tasks is used to estimate the contribution of both components to recognition judgements. Erroneously accepted old items from the to-be-rejected list indicate that the item evokes familiarity but no recollection. Stimulated by Jacoby's proposal, multinomial approaches to modelling participants' decisions have been developed which give better estimations of familiarity and recollection, and which also take guessing into account (Buchner *et al.* 1997).

Finally, research on **source memory** needs to be discussed in this context. Studies on source memory distinguish between item memory and memory for the context in which the item was presented (i.e. its source). Research on source memory has isolated many factors that differently influence item and source memory, and thus has demonstrated that these are two separable aspects of remembering (reviewed by Johnson *et al.* 1993). Ageing, for example, exerts differential influences on item and source memory. In childhood and old age, source memory is more strongly impaired than item memory (Czernochowski *et al.* 2005; reviewed by Zacks *et al.* 2000). The association-deficit hypothesis of memory in the elderly (Naveh-Benjamin 2000) generalizes this aspect of binding

between items in general (see Chapter 25) and binding of features within items (Chalfonte and Johnson 1996; see also Chapter 11). Based on such results, Johnson and Chalfonte (1994) postulated that for the conscious binding of information, as in source memory, specific higher mental processes are necessary. The concept of levels of binding described by Craik (Chapter 23) develops this idea further.

Item and source memory also differ with respect to **retrieval requirements**. Successful memory performance requires the initiation and maintenance of task-specific retrieval strategies, for which prefrontal brain areas are relevant. Several recent studies that examined neural activity in the test phase of item and source memory tasks found pronounced differences in event-related potentials (ERPs) over frontal scalp regions (Senkfor and Van Petten 1998; reviewed by Rugg and Wilding 2000). Similarly, the requirement to retrieve item-context bindings (as in source memory tasks) gives rise to a pronounced negative ERP slow wave over posterior parietal regions, which is known as the late posterior negativity (LPN). It starts around the time of the subject's response and is absent when items rather than attribute conjunctions have to be retrieved. It has been proposed that the LPN may reflect the search for or retrieval of attribute conjunctions from long-term memory (reviewed by Johansson and Mecklinger 2003).

In addition to experimental memory research, progress in **cognitive neuroscience** and new methodological developments in functional brain imaging have promoted research on familiarity, recollection, and binding mechanisms. Cognitive brain research quickly expanded and obtained increasing evidence that different states of remembering are mediated by different brain systems and binding mechanisms. Early indications of the relevance of specific brain structures for memory came from patient HM, who suffered anterograde amnesia after resection of medio-temporal brain areas for treatment of epilepsy (Milner 1958). Later, more differentiated analyses of the effects of selective impairments of memory revealed that specific brain areas are relevant for different memory processes and binding mechanisms. Mayes et al. (2004) described patient YR, who had suffered a selective bilateral hippocampus atrophy which left adjacent temporal lobe structures unaffected. She showed a selective deficit in a subgroup of association memory tests requiring the binding of items of different kinds, whereas her memory for items and intra-item associations was largely unaffected. This suggests that, while the hippocampus is engaged in the encoding and retrieval of memory records composed of arbitrary features, adjacent medial temporal lobe structures may mediate binding of features within an item and representations of unitized associations. This form of binding is preserved after

hippocampal damage and may give rise to a familiarity signal in the respective brain structures.

In this view, the hippocampus appears to be specifically relevant for recollection, whereas perirhinal structures provide the familiarity signal (Aggleton and Brown 1999; for an updated review see Chapter 16). However, alternative positions have also been put forward, as demonstrated in Chapter 19. Two main controversies can be noted. The first refers to the relevance of the hippocampus for non-episodic declarative memory, i.e. semantic memory (see Chapter 2). The second addresses the issue of whether familiarity and recollection are qualitatively different memory states in the sense that they are mediated by different brain structures and binding mechanisms, or whether they are quantitatively different expressions of one and the same declarative memory system. Proponents of the latter position quote in support of their view that hippocampal impairment influences not only recall, i.e. recollection, but also recognition, i.e. familiarity (Wixted and Squire 2004).

While these ideas about the brain systems mediating memory processes were originally derived from neuropsychological case studies and animal research, this situation was strongly changed by the development of functional brain imaging techniques. Currently, we have excellent techniques for observing neural processes correlated with memory function, with sufficiently high spatial and temporal resolution in healthy participants. ERPs allow resolution of the temporal dynamics of encoding and retrieval processes (Friedman and Johnson 2000; Mecklinger 2000), and event-related fMRI enables identification of the neural structures involved in these processes during encoding (Wagner et al. 1999) and retrieval (see Chapter20). Many examples of both methodological approaches can be found in the contributions to Parts 4 and 5.

Types of binding

Before giving an overview of the book's central topics, we will examine more closely the differences between types of binding. Although we are interested in binding mechanisms in memory, we will start with encoding and hence with perception. The simplest case is perception of an isolated object presented on an unstructured background, but even here binding is necessary. It is assumed that in perception different features, such as colour, shape, location, etc., are processed in parallel in distributed networks. The relations between these features have to be processed by means of synchronized activity within a cell assembly, giving rise to a coherent percept. Treisman postulated that these features are collected in an object file (e.g. Kahneman et al. 1992). She suggests that these files, called object tokens when representing specific objects, are the units of both working memory

and long-term memory (see Chapter 12). Therefore **'binding of features within object tokens'** is the first type of binding relevant for memory. Presumably, it operates automatically during perception if objects are attended to and separated as figures from the ground (O'Craven *et al.* 1999).

When more than one object is in view, binding between objects is required. This can be considered a higher type of binding because object tokens, the units of elementary binding processes, are themselves bound into assemblies. Context can be treated like an object; therefore between-item and item-context binding might be provided by the same process. However, one might even go one step further and classify any binding operation between explicitly encoded units, thus having the status of declarative knowledge, as between-item binding. Cabeza (Chapter 24) calls tasks in which one asks for the existence of specific information 'relational memory tasks', in order to distinguish them from item memory tasks in which relational information is not task relevant. Following his suggestion, we will call these forms of binding **'relational binding'**. Cabeza also shows that the distinction between item and relational memory is highly relevant for memory performances. However, he also demonstrates that, within relational binding, different types of relations show different effects (see also Chapter 3). Examples of features that have specific relational qualities are information on an item's perceptual characteristics, the perceptual elaboration of an item, the generation of cross-modal information, the processing of spatial relational information, the item context, and temporal relational information. According to this analysis, it is not justified to consider all types of relational binding as equivalent, although they are frequently treated as homogeneous. One consequence of this shortcoming is that in experimental research, the features which are critical for relational binding are often selected by chance and are rarely systematically compared because differences are not considered.

A further relevant dimension for the analysis of binding arises from the fact that objects and items are usually embedded in larger units. This may be a scene or an event. Therefore it is all but clear what the actual item is (see also Chapter 10). Hence, it is important to know the characteristics which define an item and the border between item and context. Depending on the task characteristics, either the item alone or the item together with spatial, temporal, or any other contextual features may constitute the object. If indeed within-item and between-item binding effects differ, and thus the outcome depends on whether elementary features are processed as part of the same or of different items, then this border is critical (see also Chapter 26). The following example illustrates this point: Yonelinas *et al.* (1999) presented upright or upside-down faces and changed the combination of inner and outer features of faces from study to test.

At test, old faces were to be discriminated either from completely new faces or from faces constructed by rearranging features from different old faces. As participants had to discriminate between the same and recombined features, the test was classified as an associative memory test and thus was based on relational binding. There was a contribution of familiarity to recognition, estimated from ROC curves, when the faces were presented upright but not when they were presented upside down. Yonelinas *et al.* suggested that an influence of familiarity on associative recognition can be found for unitized associations, i.e. if 'items' (the features of a face in this experiment) can be treated as coherent wholes. Putting it differently, in an upright orientation faces are items, whereas when they are presented upside down, features are items. The former characteristic causes within-item binding that supports familiarity-based recognition, whereas the latter causes between-item binding and recollection-based recognition.

Thus in order to predict memory effects as a function of binding, we should know the relevant factors that constitute an item. Perceptual characteristics are one defining factor, as was shown in the experiment of Yonelinas *et al.* From this perspective, object tokens (see Chapter 12) are a good starting point for the definition of within-item binding. However, any features even across processing modalities can be constituent elements of an item, and when their relations allow grouping into a unitized association they are subject of within-item binding processes (Mayes *et al.* 2004).

Thus object tokens can be bound by relational binding into larger units, which can be called episodic tokens. Object tokens generated within a perceptual modality may influence familiarity via perirhinal structures, whereas episodic tokens need relational binding via hippocampal structures and influence recollection (Ecker *et al.* 2004). However, because objects are partially defined by interacting bottom-up and top-down processes, not only perceptual factors, but also **subject's task** and **pre-existing knowledge** contribute to the definition of an item (see also the discussion of levels of binding in Chapter 23). Therefore semantic knowledge can influence whether features are processed as within-item or between-item information. Consistent with this view, Czernochowski *et al.* (2005) recently reported an ERP correlate of familiarity for learned materials that had to be rejected in the test phase of an exclusion task, even though study and test materials were presented in different modalities (see also Nessler *et al.* (2005) for an evaluation of the putative ERP correlates of familiarity and semantic knowledge).

A third factor that plays a critical role in binding is **attention**. Because attention is often considered the glue that binds features to object tokens, one may even consider it a precondition for binding. However, attention is not a

homogeneous construct either, and it also influences memory in different ways. An effect of attention on binding at the object level was demonstrated by Reinitz and Hannigan (2001). In a sequential presentation, they found enhanced false conjunctions in face recognition when the two faces from which the rearranged features were taken were presented in an interleaved fashion so that attention switched back and forth between them during encoding. Another example is the effect of attention on relational binding in a divided attention task. It has been shown that dividing attention during encoding influences the putative ERP correlates of recollection but not familiarity (Curran 2004). In addition, the selective association deficit shown by elderly people is sometimes attributed to a selective impairment of relational binding caused by an attentional deficit. However, inconsistent with this position, young adults show equal impairment in the learning of item versus relational information under divided attention (see Chapter 25). Finally, during retrieval, attentional processes are necessary for setting up retrieval strategies and adapting retrieval to the current task demands. Therefore attention may influence memory in many ways.

The brain not only has to solve the task of binding the episodic features to items and separating different items within an episode, but also has to maintain the distinction between **episodic** and **semantic representations**, the type-token problem. Seeing a deviant exemplar, for example a blue banana, should set up a specific episodic entry, but it should not instantly change the type representation so that from this time on it is assumed bananas were blue. One solution to this problem is postulating different learning mechanisms for episodic and semantic networks (McClelland and Rumelhart 1985; see also Chapter 8). This also has consequences for the question of binding in memory. Binding of sensory features in episodic tasks should be distinguished from changes of binding in semantic representations, which are probably the basis of repetition priming (Groh-Bordin *et al.* 2005). These differences may also explain why amnesics show repetition priming effects and why they can acquire semantic knowledge (see Chapter 19).

Finally, types of binding should be differentiated in the **temporal domain**, and this should be done in at least two ways. Thus the temporal domain should be considered both as a dimension of encoding and referring to the duration of retention. The temporal encoding dimension is discussed by Brown and McCormack in Chapter 10. They suggest that time, similar to space, plays a privileged role in memory binding. Time stamps may define memory events. The temporal duration refers to the difference between temporary and long-term binding (see Chapter 9). An example of a transient process is the binding of features of seen objects during perception. Other examples are the binding of

stimulus-response codes when actions are performed (Hommel 1998; Hommel *et al.* 2001) and the separation of different streams of parallel processes in a multitasking system, which also makes it necessary to bind same-goal processes. In the latter case, the prefrontal cortex probably plays a critical role (see Chapter 26). Binding for long-term remembering is a different issue. One aspect is that the neural synchronization suggested for temporary binding has to be transformed into a more durable form of representation because otherwise, when synchronization is gone, the brain is left without a trace (Wagner 2001). For this purpose, some form of consolidation must occur. Long-range cross-cortical coordination has been discussed as a relevant factor for consolidation (Paller 2000; see also Chapter 21). Synchronization may also play an important role in this process, but it may operate at other frequency ranges than synchronization in local binding (see Chapter 5). Another aspect is that consolidation may not be achieved immediately, but in a sequence of processing steps.

Considering these different aspects of binding, it is obvious that binding in human memory is a multifaceted research topic. Several different forms of binding exist, associated with different processes. Craik (see Chapter 23) coined the term 'levels of binding' to illustrate the hierarchical organization of these processes, starting with low-level perceptual binding mechanisms, continuing with the encoding of events requiring the binding of more complex constellations of features and making necessary between-item binding, and ending at a relatively context-free semantic encoding. The levels of this hierarchy may be associated with several trade-offs. Low-level encoding is rather automatic and presumably determined by the discharges of feature-selective neurons. Thereby, the response properties of the neurons provide much direct support for grouping, so that no additional cues are necessary during encoding. In contrast, high-level encoding is more effortful and context dependent, and therefore is in need of environmental support. Ageing effects are also rank-ordered along this dimension. In good agreement with the idea of such a hierarchy, Cabeza (Chapter 24) demonstrates that a well-functioning prefrontal cortex determines higher forms of between-item binding, whereas the efficiency of these brain structures is less important for within-item binding.

We can go one step further. At the computational level, Li and Lindenberger (Chapter 11) show that between-item binding (association) can be selectively impaired while leaving within-item binding intact. One critical variable in their model is the gain parameter, i.e. the adjustment of connections between units according to the feedback during learning. If they are correct and gain is related to the availability of specific neurotransmitters, the efficiency of between-item binding would finally be limited by a neurochemical factor.

In summary, differences between types of binding seem to exist at all levels of analysis. At the behavioural level, we find differences according to the types of binding that are task relevant, and from a first-person viewpoint these different types of binding are associated with different states of experience. Correlates of these processes can be found in electrophysiological signals of familiarity and recollection. Different neural structures (the perirhinal structures and the hippocampus, respectively) are suggested as sources of these electrophysiological changes. Results from brain imaging as well as neuropsychological case studies are in good agreement with these assumptions. Additionally, prefrontal brain areas seem to be relevant for active volitional binding during encoding and for an adjustment of retrieval orientation. These processes modulate the mediotemporal binding mechanisms. Analogous differences may exist in computational modelling, with more or less straightforward relations to neurochemical mechanisms. The latter differences would explain why binding processes can be selectively and gradually impaired without specific damage to the hippocampus. The contributions to this book develop these different views and demonstrate that we have made a real step forward in grounding a neurocognitive model of binding in memory.

The contributions: mechanisms of bindings and their variations

The book is organized into five thematic parts focusing on specific aspects of binding. Parts 1 and 2 deal with the neural mechanisms of binding and related computational models. On the basis of recent neurocognitive evidence, Part 1 provides a comprehensive overview of the neural mechanisms of binding. In Part 2, binding mechanisms are discussed from a computational point of view. Part 3 addresses binding in different cognitive domains, as well as the passage from transient to permanent binding states. Part 4 provides in-depth analyses of binding during episodic retrieval. Finally, Part 5 describes normal and pathological changes of memory in ageing and Alzheimer's disease, and their relation to various binding mechanisms.

The chapters in Part 1 address various mechanisms of feature binding. Eichenbaum (Chapter 2) presents evidence that the hippocampus is involved in different forms of relational binding including non-episodic declarative (semantic) knowledge. In contrast, Trinkler *et al.* (Chapter 3) see this brain structure as mainly involved in episodic but not semantic binding. Tucker and Luu (Chapter 4) discuss different forms of binding from the perspective of their adaptive utility, including the modulatory aspects of limbic networks which may serve a gating function. The next three chapters relate the mechanisms of binding to

synchronizations in specific frequency bands and/or brain structures. Klimesch (Chapter 5) presents evidence for a contribution of theta frequencies to memory formation, and for the nesting of higher frequencies in lower ones during memory encoding. Düzel *et al.* (Chapter 6) discuss theta, delta, and gamma oscillations and their covariance in relation to binding and the different electrophysiological correlates of memory. Finally, Fernandez and Fell (Chapter 7) present data from depth electrodes, demonstrating that rhinal–hippocampal synchronization contributes to memory formation. In these contributions it becomes apparent that different neural structures and different mechanisms mediate different types of binding.

Part 2 presents various computational approaches to binding mechanisms. A variety of computational models that formalize binding processes are presented. Cer and O'Reilly (Chapter 8) present a complementary learning model that allows gradual adaptation of low-level conjunctions during generalization in semantic learning tasks, but also fast learning of higher-order bindings in an episodic task. A transient binding in working memory is suggested as a third form. Similarly, Murre *et al.* (Chapter 9) discuss different mechanisms for binding in long-term and working memory. Brown and McCormack (Chapter 10) consider the role of time in these binding processes. Finally, simulating ageing effects in a computational network, Li and Lindenberger (Chapter 11) demonstrate a selective impairment of relational binding and spared within-item binding mechanisms, and discuss how these effects are related to dopaminergic neuromodulation. In sum, the approaches covered in this part support the view that human memory needs multiple and interactive binding mechanisms to function effectively.

The contributions in Part 3 deal with binding processes in perception and knowledge representation. As an integral part of encoding operations, these processes partially determine the input of memory processes. Treisman (Chapter 12) gives an overview of her research on feature integration and also demonstrates how these processes may define object tokens as entries in working memory. Rösler *et al.* (Chapter 13) use the N400, an ERP component associated with semantic processing, to examine binding processes during fact retrieval in arithmetic tasks. Using an individual differences approach, Voss *et al.* (Chapter 14) show that top-down influences can modulate binding processes. Similarly, Fujiwara and Markowitsch (Chapter 15) discuss the binding of episodes to the self and show influences of negative emotions on autobiographical memory and autonoetic awareness. Taken together, the chapters indicate that binding not only plays an important role in perception, but also contributes to the formation of durable memory traces that can be modulated by emotions.

Part 4 addresses binding processes during episodic retrieval. Retrieval, the process by which memory information is made available for behavioural responses, can be triggered automatically by appropriate retrieval cues. In other instances, control processes responsible for the specification of retrieval task parameters and/or the verification of retrieved information are required for successful task performance. Brown and Warburton (Chapter 16) show how the perirhinal cortex and the hippocampus may contribute to familiarity and conscious recollection, respectively, suggesting that different binding mechanisms are influenced by different neural processes and parameters. The same differentiation is suggested by Quamme et al. (Chapter 17) on the basis of behavioural data. Curran et al. (Chapter 18) review work on the putative ERP correlates of familiarity and recollection, and discuss the role of binding for both processes. Knowlton and Eldridge (Chapter 19) review the role of the medial temporal lobe in declarative memory, including neuropsychological case studies and brain imaging data, and also giving some credit to controversial topics. In contrast, Nyberg's focus (Chapter 20) is not the binding process itself, but the content that is bound, i.e. the modality of the stimulus. He shows that the same modality- specific structures that encode information are also active during retrieval. Next, Paller (Chapter 21) discusses various forms of binding fragments represented in multiple neocortical zones in different memory tasks and their ERP correlates. Declarative memory binding and cross-cortical storage are discussed as critical components of episodic memory. Finally, Bäuml (Chapter 22) shows that retrieval is not only the reactivation of old traces, but rather can be considered a constructive process during which memories are changed by new binding processes which may cause other information to be forgotten. Overall, the contributions of this part give an exhaustive picture of binding processes during episodic retrieval, and they sketch the neural structures mediating these binding mechanisms.

Part 5 extends these discussions to binding mechanisms in the ageing brain. Episodic memory deficits are present in normal ageing and in Alzheimer's disease. It is shown that in normal ageing strategic and associative components of episodic memory are more impaired than non-strategic components. Specifically, item-context or, more generally, associative binding appears to lose efficiency in old age. In Alzheimer's disease, episodic memory decline is less selective and more pronounced. Craik (Chapter 23) demonstrates that reduced processing efficiency may impair memory and binding in various ways. These and other results lead to his concept of 'levels of binding'. Similarly, Cabeza (Chapter 24) identifies a relational binding deficit as the main memory impairment of elderly people, and he relates this to a reduced processing efficiency of the prefrontal cortex. In Chapter 25, Naveh-Benjamin presents a series of data showing that this impairment leads to an association deficit which is specific to

the elderly and difficult to simulate by dividing attention in younger adults. McDaniel *et al.* (Chapter 26) also focus on prefrontal processes and show that the type of relation that is processed is also relevant. Friedman (Chapter 27) makes the same point concerning relational processing. He reviews a series of data that support the view of a specific deficit of conscious recollection in the elderly. In the closing chapter, Small and Bäckman relate binding to preclinical symptoms of Alzheimer's disease (AD). The results are still ambiguous, but suggest that memory impairments in preclinical AD may be less specific than previously assumed. Therefore normal ageing may be associated with a specific impairment of relational binding (associative deficit), whereas AD appears to cause a global binding impairment.

A short summary and some unresolved issues

The contributions to this book demonstrate that we already know a great deal about the relationship between binding and memory. However, many details of binding processes are not yet fully understood.

We can distinguish different types of binding. A main distinction is the one of within- and between-item or relational binding. The former type of binding is associated with familiarity and the latter with recollection. It is conceivable that the latter type of binding may even be associated with declarative knowledge in general, and not specifically tied to episodic knowledge. On the neural level, the former type of binding, and the familiarity signal associated with it, is mediated by perirhinal structures, whereas hippocampal processing is involved in the latter type of binding. However, these mediotemporal structures are not stores of memory traces; they only provide the mechanisms which bind contents represented in modality-specific processing areas. Correlates of these components can be found in electrophysiological and brain imaging data. Additionally, prefrontal areas play a critical role in memory formation and retrieval. They exert a top-down influence on binding mechanisms by specification of retrieval cues, initiation of memory search, and selection of task-appropriate ensembles of bound features. Another factor that influences the efficiency of binding may be the energetic level, for example the availability of neurotransmitters. They may influence binding by modulating the synchronization between different brain areas. For example, stress hormones and the amygdala have been shown to be important modulators of memory consolidation for emotional events (Cahill and McGaugh 1998). These synchronizations are possible mechanisms for transient binding, and oscillations in different EEG frequency bands may support grouping operations at different levels of the processing hierarchy. These levels may also differ in the distances between neural structures across which information is

bound—local versus long range. These temporary forms of binding have to be consolidated for long-term memory.

The different chapters in the book provide excellent overviews of the details of these processes, and so it is not necessary to reiterate all of them here. We only want to highlight some topics that can be found in several papers, and we also want to mention a few issues which in our view have not yet attracted the necessary attention. In the following, we briefly discuss some of these topics, hoping to instigate further research in these areas.

The first issue is the **different types of relational binding**. In this book, there are several allusions to the suggestion that relational binding is not homogeneous (e.g. Chapters 3, 10, 20, and 23–26). Bindings of locations/spatial context, temporal context, and different items seem to be different. Similarly, within- and cross-modal features differ, and modality also plays a role. Considering these differences, we argue for a more systematic analysis of different types of binding within the same experiment, across different memory tasks. This would not only result in a better understanding of binding differences, but would also add to the understanding of association memory deficits in elderly people (see Chapters 25 and 26). Additionally, we suggest multi-method studies. If the same task is investigated by means of behavioural, electrophysiological, and brain imaging techniques in parallel, we may be able to disclose the brain–behaviour relationship with respect to binding mechanisms.

A second issue is the **definition of an item**. We need an independent definition of an item if we want to explain differences in behaviour by the difference between bindings of within-item and between-item features. This definition probably cannot be given on the basis of the input structure alone, although considering results from perceptual psychology is a first step in that direction (see Chapter 12). The examination of structural and functional connectivities between selected brain areas may be a promising next step in this quest. Top-down processes, pre-semantic knowledge, task demands, etc. are modulating factors that play an important role in the flexible adaptation of bound representations to changing task and environmental demands (see Chapters 3, 14, 25, and 26). It follows from this that the analysis of binding mechanisms must be extended to other domains of memory (see Chapter 13), in particular working memory (see Chapters 8 and 9).

A third issue is the distinction between **familiarity** and **recollection**, or more generally the question of the relationship between **states of memory** and **awareness**. It is still not clear what these mechanisms are and what types of processes their correlates reflect (see Chapters 17, 18, 21, and 27). A relevant aspect here is the definition of the mental processes and their computational basis that generates

these signals (e.g. O'Reilly and Norman 2002). Another aspect is the relationship between episodic and semantic tasks. We need to explicate in what respect episodic declarative knowledge is different from semantic declarative knowledge (see Chapters 2, 3, and 19).

It is assumed that familiarity is based on a global match that may be associated with cognitive impenetrability (Fodor 1983) and hence the absence of declarative knowledge. Familiarity seems to be sensitive to intra-item binding mechanisms that lead to memory representations of unitized associations. However, the circumstances under which unitization of features into a coherent representation occurs are poorly understood. Familiarity reflects a quantitatively graded memory signal, while recollection reflects the retrieval of qualitative information from a study episode, i.e. declarative knowledge. Therefore the availability of declarative and context-rich knowledge seems to be critical for recollection but not for familiarity.

A final issue we want to mention is the distinction between **transient bindings** and more **durable bindings**. The existence of these two forms of binding has at least two consequences. First, different mechanisms probably bind features for different ranges of time (Chapters 5, 8, and 9). Further, as yet undiscovered physiological mechanisms may pertain to more extended time intervals (Arshavsky 2003). Having identified different binding mechanisms necessitates an additional process of **consolidation** that transforms transient into durable bindings (Chapter 21). We are only at the beginning of understanding these processes at the systems level, even though at a cellular level the importance of long-term potentiation for trace consolidation is undisputed (Zalutsky and Nicoll 1990). We partially understand correlates of encoding that cause successful remembering in long-term memory, at least for intervals used in the laboratory (Chapters 6, 7, and 24). However, these are only correlates. We do not really understand the neural states triggering those neural processes that enable effective and long lasting bindings. In other words, we need to understand the gating mechanisms that facilitate and enable binding to occur in the first place. Emotional qualities, personal relevance of an event, and its relatedness to the observer's self may be relevant variables in this regard (see Chapters 4 and 15). In order to learn more about this pivotal issue, experiments with enhanced personal relevance of the material and extended retention intervals seem desirable.

Therefore we expect that more veridical and ecologically valid theories of memory will emerge in the future. These theories will allow suggestions to be made for a more efficient memory encoding based on a neurocognitive model. They will also account for memory impairments, individual differences in memory performance, and ontogenetic changes in memory functioning, and they will

provide clues about ways to enhance memory functioning. Whatever form these theories take, binding mechanisms will occupy a central place. Hence, we are confident that some of the key elements of such future theories can and will be found in the contributions to this book.

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Handbook of binding and memory: perspectives from cognitive neuroscience

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Preface

The idea for this book originated at the conference *Binding in Human Memory: A Neurocognitive Approach,* which took place in 2002 at Saarland University in honour of Johannes Engelkamp and his contribution to memory psychology. The conference was also the opening event for Research Unit 448, 'Binding: Functional Architecture, Neural Correlates, and Ontogeny' funded by Deutsche Forschungsgemeinschaft (German Research Foundation). The aim of the conference was to establish the theoretical and empirical basis of a neurocognitive model of memory. For that purpose, the editors brought together two groups of researchers: those investigating memory processes mainly with experimental methods, and those using ERP/EEG and functional imaging techniques. The specific focus on binding was chosen because we consider this process a core operation in human cognitive and neural processing.

The conference strengthened our view that feature binding is a fundamental process in perception and memory, and that the exploration of binding mechanisms may help to extend our understanding of key memory processes such as encoding, consolidation, and retrieval. We asked the conference participants as well as a number of other researchers for contributions to a book on this topic. As the feedback from the authors and from the external reviewer was very positive, Oxford University Press decided that the book should be published.

The result is the present book comprising 28 chapters on aspects of binding in different domains of memory research. The main focus is the contribution of different medial temporal lobe structures to the retrieval of episodic information, and the role of familiarity and recollection in remembering. Another focus is the neural mechanisms of binding. In these chapters the authors discuss how binding might emerge from neural processing. A core concept in this regard is the synchronization of neural activity which may support different functions depending on synchronization frequency.

The contributions to this book provide an exhaustive survey of recent views on binding and its importance for remembering. In addition, they provide a promising approach offering an integrative view of the functions of binding in