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Meta-analysis of the research impact of Baddeley's multicomponent working memory model and Cowan's embedded-processes model of working memory: A bibliometric mapping approach

Abstract: In this study bibliometric mapping method was employed to visualise the current research trends and the impact of the two most influential models of working memory, namely: A. D. Baddeley and G. J. Hitch's (1974) multicomponent working memory model and N. Cowan's (1988) embedded-processes model of working memory. Using VOSviewer software two maps were generated based on the index-term words extracted from the research papers citing Baddeley (2000) and Cowan (2001), respectively. The maps represent networks of co-occurrences of index terms and can be interpreted as an indication of the main research fields related to the examined models of WM. The results of the analysis revealed that the spheres of influence of the two main conceptualisations of WM are rather different than similar. Although the first two clusters, i.e. "brain mapping" and "higher-level cognition and development" are present in both maps, their relative importance varies. The remaining clusters are unique to each map. Baddeley's theory seems to have a greater influence on "neuropsychology", while Cowan's theory – on basic research on "biological systems", including the nervous system in humans and animals. The second difference between these theories concerns their relations to functions and dysfunctions associated with particular sensory modalities: in Baddeley's theory with the "auditory modality" cluster; and in Cowan's – with the "visual modality" one.

Key words: multicomponent working memory model, embedded-processes model of working memory, meta-analysis, co-word analysis, bibliometric map

Introduction

Since its introduction in 1951 by Miller (Miller, Galanter i Pribram, 1960) the term 'working memory' has instigated one of the most vivid and extremely diverse strand of research in psychology and in cognitive neuroscience (upon its emergence). It is very illustrative to see this impact in numbers. Since 1960, Scopus database recorded almost 37,000 papers containing the term 'working memory' in their titles, abstracts or keywords. 273 reviews of various issues related to working memory research were published solely in 2015. Preparing this volume of the Polish Psychological Bulletin devoted to research on working memory, we, as the editors, were tempted to speculate on the future of this research. An

accurate diagnosis of its directions would be a valuable signpost for researchers. However, it feels beyond the scope of this editorial – if possible at all - to extrapolate from such amount of data. Instead, we decided to focus on the theoretical frameworks of WM and their impact, hoping that strengthening conceptual framework may help to find the way to new insights advancing the field.

Therefore we decided to carry out a meta-analysis of empirical work in the field of working memory research, employing the co-word bibliometric mapping approach as a powerful tool for discovering the structure of scientific inquiry (Whittaker, 1989). We analysed the scope of influence of two, in our view most influential, papers in the field, published at the beginning of the 21 century. These publications represent two theoretical

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approaches to working memory, fundamentally different in their assumptions. The first one is represented by Alan Baddeley's article "The episodic buffer: A new component of working memory?", published in 2000 in the *Trends in Cognitive Sciences*. According to the Scopus database, the article was cited in the original research papers 1,660 times by the end of 2015. The second approach was offered by Nelson Cowan in his article titled "The magical number 4 in short-term memory: A reconsideration of mental storage capacity", published in 2001 in the *Behavioral and Brain Sciences*. The Scopus database registered its 1,645 citation in the original research papers by the end of 2015. Therefore, in terms of their publication dates and citations indexes, these two papers are comparable.

Nevertheless, the papers represent fundamentally different theoretical approaches to working memory. Conceptual frameworks are integral part of all research. They provide a basis for "selection and organisation of known facts", and therefore they constitute "a crucially important guide to the direction of fruitful research" (Parsons, 1938; p. 20). However, by their very nature all theories or models are incomplete, as they simplify the natural world. Different theories will point to different research directions, predictions and methodological approaches. Thus, the aim of this meta-analysis was to construct the thematic maps of the research inspired by the two most influential models of WM, to identify both similarities and discrepancies. We hope that focusing on the theoretical frameworks of WM may help to find the way to new insights that would enable advances in the field. To begin with, in the following section we present a summary of the models of working memory under investigation.

Article published by Alan Baddeley in 2000 introduced the last version of the multi-component model of working memory so far. A key assumption of this theory is structural separateness of memory subsystems subjected to the central executive system. Precisely in this sense, it is a multi-component model. Initially (Baddeley and Hitch, 1974), the model involved three subsystems: a central executive system (CE) and two subordinate memory buffers (slave systems) – the phonological loop and the visuo-spatial sketchpad. The fundamental function of these buffers was deemed to be a short-term storage of information in the acoustic code and in the visual code, respectively.

In 2000, Baddeley complemented his model with the episodic buffer (EB), the function of which is to store complex information. The episodic buffer enables a temporary storage of integrated episodes, such as information represented simultaneously by various codes, for instance verbal and visual, taking into account a time axis. Like other memory subsystems, the episodic buffer has a limited capacity and is controlled by the central executive system, which is also responsible for integrating information from various sources into coherent episodes. In Baddeley's view, the existence of the episodic buffer is evidenced by a number of experimental studies on coding and storing complex information (e.g. Luck & Vogel, 1997), and neurobiological studies (Mitchell, Johnson,

Raye, & D'Esposito, 2000; Prabhakaran, Narayanan, Zhao, & Gabrielli, 2000). Experimental studies show that the scope of working memory is smaller for semantically unrelated words, including around five items, whereas for words constituting a meaningful sentence it may include even 15 items (Baddeley, Vallar, & Wilson, 1987). According to the researchers, semantic integration of words into a sentence also occurs in the episodic buffer.

The episodic buffer, like the other memory subsystems, participates in acquiring and retrieving information from long-term memory. It is assumed that the episodic knowledge is encoded in a comprehensive manner, considering a time axis. Episodes are encoded with their fullest possible contexts, hence the process cannot be reduced to a single code. In order to demonstrate the separateness of the episodic buffer from the long-term episodic memory and other working memory subsystems, Baddeley and Wilson (2002) refer to cases of patients with amnesia. Amnesia manifests itself by a lack of ability to encode new episodes in the LTM, whereas the short-term memory of episodes, often much more complex than stimuli stored by using the phonological loop, remains undisturbed.

Linking the central executive system with the operation of the episodic buffer is a separate problem. From Baddeley's model it appears that there is a close link between them. The author distinguished two mechanisms for creating complex episodes: passive and automatic, or active and requiring CE control. The data later accumulated suggest that the process of creating episodes, also multi-modal ones, does not require any participation of the central executive system. Baddeley's research seem to indicate that in the process of integration of elementary features of stimulation, e.g. colour and shape of visual objects (Allen, Baddeley, & Hitch, 2006), and also taking into account different sensory modalities, e.g. visual and verbal (Allen, Hitch, & Baddeley, 2009), this process occurs automatically. It turns out that various memory tasks, which used stimuli defined both by individual features and a combination of features, charge WM in a similar way. It seems that the processing unit is the entire object, regardless of the number of features defining it, and the process of integration, occurs before encoding them into the episodic subsystem.

The episodic buffer, like all the other memory subsystems, is connected by a kind of a main to the long-term memory (LTM). It is thanks to the working buffers that the working memory participates in encoding information in the long-term memory, and in its selective recalling (Baddeley & Logie, 1999). Interesting evidence, showing that the use of LTM resources occurs with participation of the central executive system, is provided by data from Gathercole's studies (1999): it was found that short-term storage of meaningless groups of letters is the more effective the more they resemble words of natural language. This indicates a significant participation of LTM linguistic structures in encoding information in working memory.

As to the embedded-processes model of working memory, Nelson Cowan presented it very elaborately in his paper in 2001. In Cowan's view, working memory is

understood dynamically, that is, as a cognitive process which is responsible for maintaining access to information necessary to carry out current tasks of the system. As in other theories, according to Cowan, working memory is a complex system. The author distinguishes two basic systems: the central executive system and a homogeneous memory system. Its homogeneity derives from the assumption that there are no sharp boundaries between short and long-term memory, and the evidence showing their separateness can be explained without postulating structural separation of memory subsystems. The results of simultaneous tasks, indicating – according to Baddeley – separateness of subsystems, can be explained by the phenomenon of interference occurring within the active information. Thus, these data do not constitute evidence of separateness of memory buffers, but only point to interference as one of the mechanisms of information loss in WM (Glass, Millen, Beck, & Eddy, 1985). More direct evidence indicating WM independence from the modality of material (domain-general memory) was provided by subsequent research by Saults and Cowan (2007). Regardless of whether the task required remembering only the visual stimuli, or only acoustic stimuli, or both kinds at the same time, the subjects were able to recall 3–4 items. According to Cowan, this is evidence for homogeneity (modality-independence) of WM system.

In Cowan's view, working memory is a temporarily active – thanks to attentional processes – part of long-term memory. Thus, we have a homogeneous memory system, but the data stored may differ in their degree of activation, which depends on the currently performed tasks. Basically, the author distinguishes three levels of activation of memory traces, and two of them are directly related to working memory. The central executive system, directing the controlled processing of information, may – thanks to the focus of attention (FA) mechanism – activate both the existing memory traces and the data coming from the external environment. In the case of memory data and some data from the environment, this process occurs volitionally – so it is top-down and endogenous. However, certain external stimuli may attract attention in a bottom-up (exogenous) way, sometimes also engaging the focus of attention. This applies, for instance, to new stimuli or those which are important to the individual for other reasons. The content covered by the focus of attention have a particular property – it is available to consciousness. Therefore, the capacity of the focus of attention is very small: around 3–4 units (portions) of information (Chen & Cowan, 2009; Saults & Cowan, 2007). The consequence of this mechanism is a new understanding of WM capacity limitation. It does not result from capacity of a storage or a buffer, but from the dynamics of the process of information activation in the focus of attention. Attentional mechanism responsible for this process allows for simultaneous activation of a small number of items. It is also very short-term: the passage of time, or shifting attention to other stimuli, rapidly decreases activation of previously activated items, and this leads to the loss of access to them, or – if they are in LTM – requires their new retrieval.

Activation of information decreases as a function of time and, unless it is raised again through the focus of attention, it quickly ceases to be available to the current processing. However, for some time the activation level is increased, and that affects processing, for instance, it is more probable that the information more activated will be covered by the focus of attention than information not activated, and will influence the ongoing cognitive processes. In this area there can also be the items of the task which are subject to habituation, because, for example they are well known or rejected as noise or distraction. Availability of this information is still high, although they are not processed consciously. The area of working memory encompassing information characterised by an increased level of activation is identified by Cowan with the short-term memory. The third level of activation described in Cowan's model is the information not activated, located in LTM. It is potentially available to the central executive system and can be activated (which is tantamount to its retrieval), but before that happens, it is not involved in information processing.

Cowan does not envisage separate structures for stimuli of different modalities. Admittedly, neurobiological data suggest separateness of brain mechanisms for processing stimuli of different modalities (cf. D'Esposito and Postle, 1999), but, according to Cowan, they are not evidence for diversity of working memory subsystems due to the kind of material. In this sense, in this WM theory the memory system is understood homogeneously. Perhaps the basis for that homogeneity is not only a shared workspace, but also – as it seems – an attentional mechanism shared for exogenous and endogenous stimuli.

The source of data indicating a more limited capacity of WM focus of attention that follows from Miller's magic number were the meta-analyses of various memory tasks performance. One of them was Sternberg's task of WM searching. Cowan (1995) argues that the reaction time to signals found in the last several positions in the set, which is significantly shorter than the reaction time to signals appearing earlier, is a proof for that. It also seems that in a set of stimuli consisting of up to four items, proactive interference does not occur (Halford, Maybery, & Bain, 1988; Oberauer & Vockenberg, 2009), or is weak (Carroll, Jalbert, Penney, Neath, Surprenant et al., 2010), regardless of their degree of phonological similarity (Tehan & Humphreys, 1995). McErlee (1998) interprets this data in favour of the thesis about privileged position of information in the focus of attention. Availability of such information is immediate and does not require any retrieving processes. However, this effect is very short-lived: it is completely eliminated by a distraction task introduced between the exposure of the series of items and the target stimulus.

Deciding which of the reviewed models is closer to truth seems very difficult if it is possible at all. Similarly problematic, if not impossible, seems to be their reconciliation. It is not our aim. Nor is it our aim to make a systematic review of all other theoretical proposals that have appeared in large numbers in the last fifteen years. We asked ourselves how these two – undoubtedly different, and

yet similarly influential – theoretical approaches inspired researchers. The objective of our meta-analysis was thus singling out and juxtaposing areas of scientific applications of both these approaches with the use of bibliometric mapping.

Bibliometric mapping is a common scientific tool for assessing the impact of a research field, an author, or a particular paper, as well as for identification of current and promising future research directions. It can be used for generating knowledge on the basis of big databases. In general, this methodology relies upon the assumption that each research field can be characterized by a list of the most important keywords (be it authors' names, citations, indexer keywords). Since the keywords can be seen as representing the contents of a paper, they are considered to be a reliable indication of the scientific concepts referenced in them, reflecting the present state-of-the-art of the scientific field under investigation (He, 1999). Therefore, terms extracted from the titles, abstracts or corpuses of a large collection of scientific papers can be used as the basic data used in order to analyse and visualize the structure of a research field. Resultant term maps indicate the relationships between concepts in a studied domain as assessed on the basis of their co-occurrences in publications. The higher the number of papers in which the two terms co-occur, the stronger is the relatedness of the constructs, indicating that the terms belong to the same research area. Thus, bibliometric maps can be used in order to measure the impact level of different sub-domains and concepts (Börner, Chen, & Boyack, 2006; Noyons, Moed, & Luwel, 1999).

In the distance-based approach for visualising bibliometric networks taken in the current paper (see: van Eck & Waltman, 2014), the strength of the link between the concepts under examination is represented as spatial distance between them: the stronger the association, the closer the spatial distribution of the terms. Furthermore, the distribution of terms on a map leads to the identification of sets of highly related concepts, i.e. conceptual clusters. Again, small distance between two clusters on the map indicates that the two conceptual fields are conceptually related. Thus, the map provides an overview of the structure of the domain under investigation (Eck, Frasinca, & Chang, 2008, van Eck & Waltman, 2011; Ecker, Lewandowsky, & Oberauer, 2014).

Method

In the current study the bibliometric mapping was employed with a use of VOSviewer software (van Eck & Waltman, 2010; van Eck, Waltman, Dekker, & van den Berg, 2010), which utilises the mapping technique based on multidimensional scaling (see: van Eck & Waltman, 2010; Eck & Waltman, 2011). It is based on a systematic literature search performed in December 2015 using Scopus database. The searched was aimed at identification of all of the papers citing Baddeley's (2000) and Cowan's (2001) articles, respectively. Only research articles from peer-reviewed journals were included. As a result, 1660 papers citing Baddeley's (2000) article and 1645 papers citing

Cowan's (2001) article met the two inclusion criteria for the study and were subsequently included into the analysis.

Based on the corpus text representing index-terms extracted from the papers, two index term maps were created. The first map represented the content of the papers referring to Baddeley's model (2000) (see: Figure 1), whilst the second map represented the content of the papers referring to Cowan's paper (2001) (see: Figure 2). The visualisations were based on the index-term words, which occurred at least twenty times within the corpus of the papers. For each of these terms the relevance score was automatically calculated by VOSviewer, and 60% of the most relevant terms were subjected to the further analysis. In result, there were 216 and 223 keywords included to the analysis in the case of Baddeley's and Cowan's paper, respectively.

Full counting method of analysis was employed. The number of clusters and the minimum cluster size were not specified. Finally, in order to obtain more accurate grouping of terms on the maps (1) different spellings of the same term were merged (e.g., 'behavior' and 'behaviour'), (2) abbreviations of terms were merged with the terms themselves (e.g., 'psz' and 'people with schizophrenia') and (3) frequently-occurring terms that possess very unspecific meaning were excluded from the analyses (e.g., 'journal', 'aim', 'purpose', 'outcome'). However, to avoid decisions that may involve a certain degree of arbitral judgements, we decided not to merge synonyms into single terms or different terms seemingly referring to the same concept (e.g., 'motion perception' and 'movement perception', or 'parietal lobe' or 'parietal cortex').

On both maps different colours indicate separate clusters, whilst the relative importance of a term based on the number and strength of all of its relationships is indicated by the font size and circle size of each item.

Results

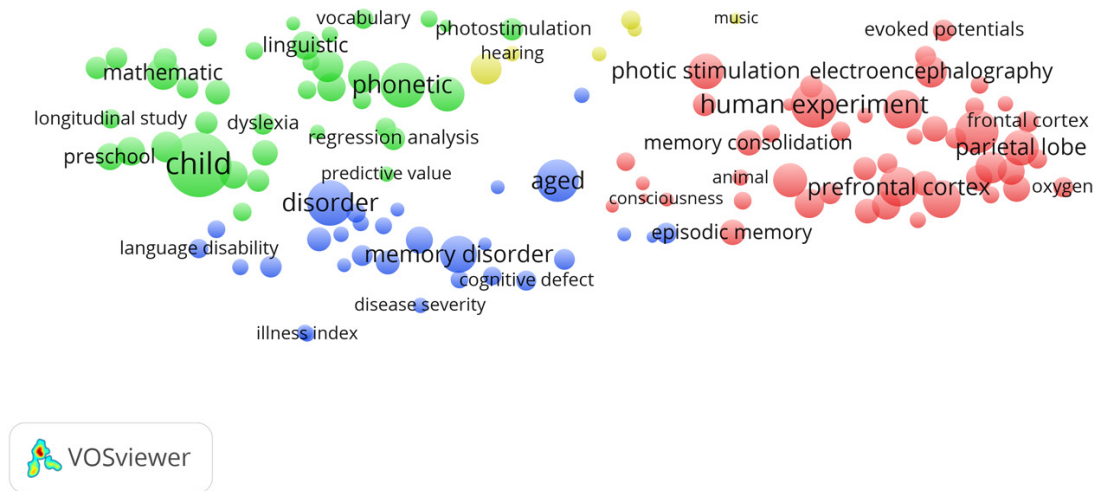
A map of the index terms co-occurrences in the research papers citing Baddeley's model (2000)

The analysis of the corpus representing index terms used in the papers citing Baddeley's formative paper (2000) indicated the existence of four separate clusters. The term-map is presented in Figure 1. The clusters were labelled as follows: (1) "brain mapping", (2) "higher-level cognition and development", (3) "neuropsychology", and (4) "auditory perception". The most important terms included in each cluster are presented in Table 1.

The first, largest cluster (in red) located on the right-hand side of the map consist of 48 concepts related apparently to the studies of the function of human brain through the use of neuroscience techniques. The most important concepts in this cluster – as judged on the basis of their number of occurrences and central location – are: 'human experiment' and 'normal human', followed shortly by 'brain mapping', 'brain' and 'brain function'. These terms are surrounded by the names of specific neuroimaging techniques and the brain structures, which presumably denote the target areas for these investigations.

Table 1. Clusters of index-terms occurring most frequently in the research citing Baddeley's model (2000). Cluster 1 – “brain mapping”, Cluster 2 – “higher-level cognition and development”, Cluster 3 – “neuropsychology”, Cluster 4 – “auditory perception”

Cluster 1	Occurrences	Co-occurrences	Cluster 2	Occurrences	Co-occurrences
human experiment	288	2070	child	452	4010
normal human	171	1476	phonetic	226	1918
prefrontal cortex	163	1513	language	131	1154
brain mapping	157	1786	comprehension	112	974
photic stimulation	148	1226	reading	109	986
brain	129	1131	mathematic	102	1071
electroencephalography	120	970	intelligence	95	942
magnetic resonance imaging	119	1400	linguistic	95	781
parietal lobe	113	1253	psychological aspect	87	780
brain function	96	860	preschool child	71	796
functional magnetic resonance imaging	93	976	language test	70	747
episodic memory	83	639	photostimulation	70	491
memory consolidation	83	625	psychometry	69	648
hippocampus	82	783	child development	68	585
visual stimulation	75	509	inhibition	65	409
Cluster 3	Occurrences	Co-occurrences	Cluster 4	Occurrences	Co-occurrences
aged	255	1778	speech perception	115	922
disorder	216	2017	auditory stimulation	46	380
memory disorder	167	1340	noise	37	225
case control study	76	706	hearing	34	235
amnesia	68	433	auditory perception	32	215
major clinical study	66	551	music	27	129
school child	64	547			
syndrome	61	429			
attention deficit disorder	57	460			
schizophrenia	57	436			
cognitive defect	53	398			
Alzheimer disease	47	304			
cognition disorder	41	331			
reproducibility	41	367			
questionnaire	37	233			

Figure 1. A map of the recurring index terms in the research citing Baddeley's model (2000)

On the basis of the techniques several subfields can be identified within the cluster. Thus, ‘electroencephalography’ is closely associated with the related terms such as ‘event related potential’ and ‘evoked potentials’, or ‘cerebral cortex’. Furthermore, ‘brain mapping’, a central term for another subfield, is closely associated with ‘magnetoencephalography’ (MEG) and ‘functional magnetic resonance imaging’ (fMRI). These items are located in close proximity to nodes such as: ‘frontal lobe’, ‘temporal lobe’ (most strongly connected to MEG) and ‘parietal lobe’ or ‘parietal cortex’ (more closely related to fMRI). Additionally, moving to the bottom area of the cluster, another set of interrelated terms can be found, such as: ‘magnetic resonance imaging’, ‘transcranial magnetic stimulation’ and ‘nuclear magnetic resonance imaging’ located closely to ‘hippocampus’, ‘prefrontal cortex’ and ‘temporal lobe’. Finally, the terms: ‘consciousness’, ‘animal’, ‘theory’ and ‘information processing’, are included to the “brain mapping” cluster.

The second biggest cluster (grouping 38 items) – “higher-level cognition and development” – is located on the left-side of the map (in green). The most important concept here – ‘child’ – is surrounded by such terms as: ‘education’, ‘preschool’, ‘longitudinal study’, ‘child development’ and ‘dyslexia’. Taken together they are representative of cognitive developmental studies. Another subfield of this cluster is related to language investigation. It consists of the central term – ‘phonetic’ – linked to terms such as: ‘reading’, ‘linguistic’ and ‘vocabulary’. It is interesting to note that ‘phonetic’ is also located next to the term ‘hearing’, although ‘hearing’ belongs to the separate cluster.

The third cluster (in blue) – “neuropsychology” – is located at the bottom of the map. The most relevant concepts here are: ‘aged’, ‘disorder’ and ‘memory disorder’, as well as less frequent ‘cognitive defect’, ‘disease severity’, ‘amnesia’, ‘illness index’, ‘attention deficit disorder’ and ‘language disability’. Interestingly,

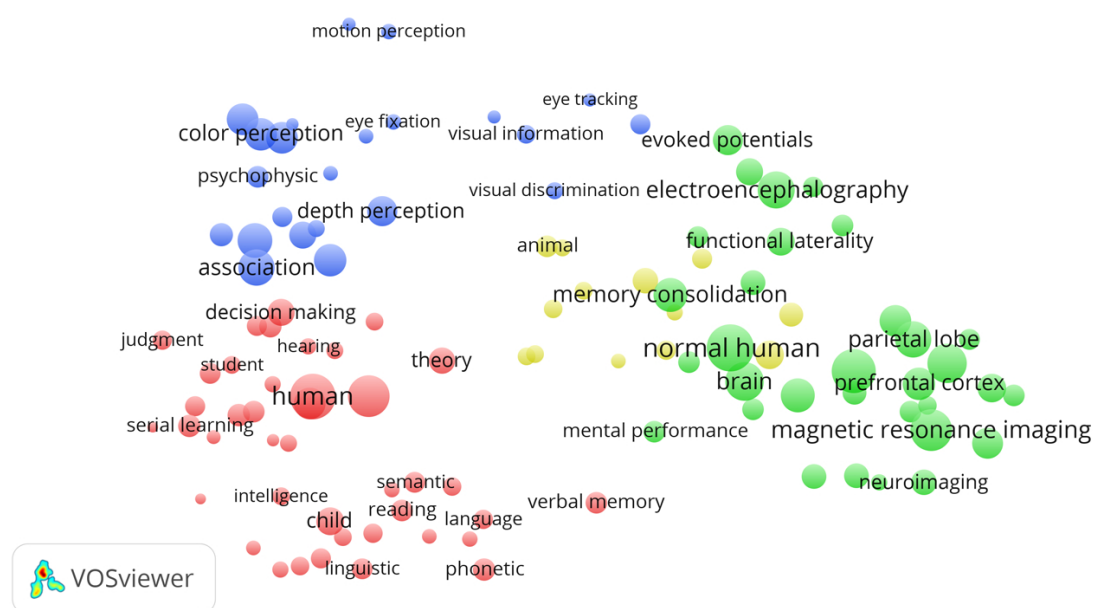
terms such as ‘school child’ and ‘intelligence test’ are also included here. However, they are located in a close proximity to ‘attention deficit disorder’ and ‘language disability’ on one hand, and – on the other hand – to the subfield representing cognitive developmental studies, which belongs to the second cluster.

Finally, the smallest cluster (in yellow) represent studies on hearing or auditory perception of speech or musical sounds. It consists of six following, strongly associated concepts: ‘speech perception’, ‘auditory stimulation’, ‘noise’, ‘hearing’, ‘auditory perception’ and ‘music’.

A map of the index terms co-occurrences in the research papers citing Cowan's model (2001)

The analysis of the corpus representing index terms used in the papers citing Cowan's (2001) also revealed the existence of four separate clusters. The term-map is presented in Figure 2. The following clusters were identified: (1) “higher-level cognition and development”, (2) “brain mapping”, (3) “vision research”, and (4) “biological models”. The most important terms included in each cluster are presented in Table 2.

The first, largest cluster located on the left-hand side of the map (in red) consist of 43 concepts related apparently to the higher-level cognition, such as ‘learning’, ‘decision making’, ‘intelligence’, ‘reading’, ‘language’, ‘judgement’, ‘problem solving’ and ‘child development’. ‘Learning’ as the most central and – by the virtue of its appearance – seemingly most important term in this cluster is displayed in a close proximity of ‘intelligence’. The bottom area of the cluster seems to represent research on language acquisition, as it is dominated by the relatively important term ‘child’ (together with the associative term ‘age factor’ and more peripherally located term ‘school child’) placed in close proximity of terms such as ‘language’, ‘linguistic’, ‘phonetic’, ‘speech perception’, ‘knowledge’ and

Figure 2. A map of the recurring index terms in the research citing Cowan's model (2001)

'education'. The top area of the first cluster groups together terms such as 'decision making', 'judgement' and 'problem' and 'problem solving' – i.e., the processes representing higher cognitive functions.

The second largest cluster (in green) located on the right-hand side of the map represents research on "human brain mapping". It consists of 37 terms. The central concept in this cluster is 'normal human' which presumably denotes a major population under these investigations. Overall, the structure of this cluster seems very clear. The terms related to studies on electrical activity of the brain and studies related to neuroimaging tend to form separate subfields. The first subfield (located in the upper area of the cluster) is represented by the most central item: 'electroencephalography', and related concepts such as 'electrophysiology', 'evoked potentials' and 'event related potential'. They are located closely to such terms as 'visual cortex', 'functional laterality' and 'selective attention'. It is interesting to note that this subfield is aligned to the "vision research" cluster. The second subfield representing neuroimaging studies includes the following terms related to methods: 'magnetic resonance imaging', 'functional magnetic resonance' and more global 'neuroimaging', accompanied by the brain structures, such as: 'parietal lobe' and 'parietal cortex', 'frontal lobe', 'prefrontal cortex', 'temporal lobe' and 'hippocampus'. Finally, the left-hand side of the cluster is occupied by more sparsely distributed terms related to behavioural performance measures, such as 'mental task', 'mental performance' or 'reaction time'.

The content of the third – "vision research" – cluster located at the top of the map (in blue) is composed of 24 terms. The content of this cluster also appears very consistent. The major theme is represented here by the most important terms grouped together and located most centrally, i.e., 'colour vision', 'colour perception',

'orientation' and 'psychophysics'. Interestingly, two other subfields can be identified here. The first set of terms is related to perceptual or associative learning. This subfield can be exemplified by terms such as: 'discrimination learning', 'perceptive discrimination', 'association learning', 'visual discrimination' or by the most dominant general terms within this area: 'association' and 'cue'. Most interestingly, this subfield is located peripherally at the bottom side of the "vision research" cluster, and seems to gravitate toward the 'concept formation' and 'decision making' components of the "higher-level cognition" cluster. The second, very coherent subfield within the "vision research" cluster represents investigation on eye movement. It consists of the concepts such as 'ocular', 'eye fixation', 'saccadic eye movement' and 'eye tracking'. Interestingly, this subfield is located most peripherally (at the upper left) within the third cluster and adjoins the 'electroencephalography' subfield of the "brain mapping" cluster, which is suggestive of a certain degree of shared methodology and interests within the subfields.

Finally, the fourth, smallest cluster on the map (in yellow) – consisting of 15 terms – seems to represent "biological modelling" or non-human research in psychology and cognitive science. The major terms grouped here are: 'animal', 'computer simulation', 'neural network', 'mathematical model', 'biological model'. Thus, these terms speak to modelling of biological systems, including particularly challenging tasks such as cellular models of brain functioning (as indicated by the terms 'nerve cell' or 'nerve net') or biological accounts of 'consciousness'. It is interesting to note that although this cluster is the smallest in terms of a number or corresponding nodes, it is located at the centre of the map, indicating perhaps the most fundamental and basic status of this research, and its relatedness to all other areas of investigation.

Table 2. Clusters of index-terms occurring most frequently in the research citing Cowan's model (2001). Cluster 1 – “higher-level cognition and development”, Cluster 2 – “brain mapping”, Cluster 3 – “vision research”, Cluster 4 – “biological models”

Cluster 1	Occurrences	Co-occurrences	Cluster 2	Occurrences	Co-occurrences
learning	253	1620	normal human	199	1499
child	181	1177	electroencephalography	198	1343
decision making	141	729	brain mapping	163	1719
theory	108	637	brain	161	1462
intelligence	72	411	parietal lobe	128	1256
psychological model	70	295	memory consolidation	115	782
student	68	325	magnetic resonance imaging	111	1192
phonetic	67	574	functional magnetic resonance imaging	106	1018
problem	67	437	prefrontal cortex	104	923
reading	66	545	brain function	92	783
language	65	464	evoked potentials	89	669
speech perception	56	512	event related potential	73	511
semantic	55	447	brain region	65	669
clinical trial	55	287	functional laterality	55	565
learning	253	1620	normal human	199	1499

Cluster 3	Occurrences	Co-occurrences	Cluster 4	Occurrences	Co-occurrences
visual stimulation	146	908	system	158	793
association	136	876	animal	74	514
orientation	132	859	nerve cell network	55	605
cues	116	804	computer simulation	55	397
colour perception	102	645	neurological	51	440
colour vision	92	614	neural network	47	383
psychophysics	85	451	consciousness	42	390
discrimination learning	81	566	prediction	37	292
perceptive discrimination	74	477	computer	36	276
visual field	42	334	nerve net	35	390
awareness	38	266	nerve cell	35	264
visual information	38	230	mathematical model	35	235
association learning	37	274	algorithms	24	157
visual discrimination	35	224	biological model	22	207
visual stimulation	146	908	system	158	793

Discussion

Although maps stemming from the co-word analysis are considered as very difficult to interpret (He, 1999; van Eck & Waltman, 2014), it does not seem to be the case in the current analysis. The clusters revealed here seem both clear and coherent as they apparently form meaningful constellations. It enable us to make direct comparisons between the research subfields inspired by the WM models under investigation. The comparisons discern both a certain degree of similarity between the research, as well as a certain degree of diversity.

In terms of the similarities, two biggest clusters – i.e., “brain mapping” and “higher-level cognition and development” – emerged on both maps and indicate the main research trends inspired by the two WM models under investigation. In the case of research inspired by Baddeley’s WM model, brain mapping area is more strongly represented, whereas in the case of Cowan’s article the cluster related to the studies on higher-level cognition and development is more noticeable.

These two clusters may indicate main research trends in the area of studies on working memory for which a particular WM theory is crucial, or – paradoxically – is not very important. The first possibility seems obvious when research concerns theoretical choices between competing approaches in reference to neurobiological data and brain substrate of WM. However, such studies are not very common in this area. More often brain activity (particularly in the regions of parietal cortex, prefrontal cortex and hippocampus), registered in studies devoted to other research questions, is interpreted as associated with working memory functions. In that case, a particular theory of WM is not really important for researchers. This conclusion can be supported by the systematic review presented by Kudlicka and colleagues (Kudlicka, Clare, & Hindle, 2011) aimed at identifying issues critical for improving field consistency in the studies on executive deficits in early Parkinson’s disease. The review revealed that only a few studies included in the analysis grounded their methods in a formal theory of executive function. It turns out that in this particular area researchers refer to Baddeley’s theory more often than to Cowan’s (see: Kudlicka et al., 2011), perhaps viewing it as longer and more firmly rooted in psychology. However, even more often, they do not refer to any particular theory at all.

Additionally, from the perspective of higher-level cognition and development studies, references to particular WM theory may not be as important as, for example, research paradigms used in operationalization of variables linked to WM.

Major differences between the research areas inspired by the WM models under consideration were related to the smaller clusters. The third revealed area of application of Baddeley’s WM model was “neuropsychology”. It seems that, again, the key factor is the “primacy effect” of Baddeley’s theory, but also its greater facade accuracy, as compared to Cowan’s theory. Abnormalities observed by neuropsychologists are often associated with the impaired

processing of stimuli of particular modality. Reference to independent WM buffers distinguished in Baddeley’s theory is then more intuitive than reference to Cowan’s homogeneous model. Admittedly, both theories cope well with neuropsychological kind of data (Orzechowski, 2012), but for researchers who are not specialists in the field of cognitive psychology, Baddeley’s theory is simpler. It may also be significant that some of Baddeley’s own work was related to neuropsychology (Baddeley, 1982; Tamlyn, McKenna, Mortimer, Lund, Hammond, et al. 1992; Vallar, Papagno, & Baddeley, 1991; see: Baddeley, 2013 for review).

In a similar vein, the “auditory perception” cluster appeared to be another area of application specific only for Baddeley’s WM model. This is clearly related to the fact that the mechanism of phonological loop and the so-called internal reviews, crucial in auditory perception and speech perception in particular, was described in great detail by Baddeley and tested for over 40 years.

Interestingly, the “vision research” cluster revealed in the analysis of texts citing Cowan’s model (2001) is absent on the map representing research areas inspired by Baddeley’s WM model (2000). Although Baddeley’s model includes a visual-spatial subsystem alongside with phonological loop, it seems that in this case Cowan’s model proves to be more useful. Perhaps this is due to the attentional mechanism postulated both by the studies of perception and orientation on one hand, and by Cowan’s theory on the other. Even if we do not know the extent to which they are the same mechanism, mutual relations between these areas of research, even if based solely on inspiration (cf. Orzechowski, Nęcka, & Balas, in this volume), are very close.

Finally, the “biological models” cluster was revealed only in the case of studies inspired by Cowan’s WM model, but not by Baddeley’s WM model. This cluster represents a broad group of studies on natural biological systems and systems imitating natural ones. In general, Cowan’s theory seems to be more attractive for such purposes, probably due to the so-called biological credibility. The mechanism of activating cognitive representations, which makes them temporarily available (e.g. to higher cognitive processes), has its biological equivalent in the form of a precise and economical mechanism of activating brain structures. In this way, there are also e.g. neural networks, which are a kind of computer simulations.

In summary, the results of bibliometric mapping analysis undertaken here has revealed that the spheres of influence of the two main conceptualisations of WM are rather different than similar. Although the first two areas, i.e. “brain mapping” and “higher-level cognition and development” are present in both maps, their relative importance is different. The other clusters are completely different. Baddeley’s theory seems to have a greater influence on neuropsychology, while Cowan’s theory – on basic research on biological systems, including the nervous system in humans and animals. The second fundamental difference between these theories concerns their relations to functions and dysfunctions associated with particular sensory modalities: in Baddeley’s theory with the auditory

modality, and in Cowan's – with the visual modality. To our knowledge this is the first visualisation of the impact of the two models of WM.

It is important to note that the quality of the results of co-word analysis depends on a variety of factors, such as the quality of words themselves, the scope of the source data, and the statistical methods chosen for representing the findings (He, 1999). One serious concern addressed by many researcher (see: He, 1999, for discussion) is the so-called indexer effect, which refers to the fact that keywords assigned to the papers – even by the trained indexers – may be out of date (e.g., they may reflect the conventional views on the field and thus hinder novel term uses). However, as He (1999) argues, in the co-word analysis the most important aspect of a term is not its meaning itself, but its linkages with other words. Another problem relates to the trade-off between the size of the cluster and the level of analysis (Rafols & Meyer, 2010). In result of this trade-off some topics may not be reflected on a map. One example could be the issue of the effectiveness of cognitive trainings. It is apparently a hot topic in the current working memory research, nevertheless – not represented on our maps. This lack of correspondence may indicate that training studies are atheoretical, i.e., unrelated to any specific theoretical approaches, which is an interesting conclusion to be checked. Finally, the understanding of the resultant maps depends heavily on the user's visual interpretations (van Eck et al., 2008) and requires certain degree of expert judgment (van Eck & Waltman, 2014).

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