Consciousness and Cognition xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Consciousness and Cognition

journal homepage: www.elsevier.com/locate/concog

Review article

Merging with the path not taken: Wilhelm Wundt's work as a precursor to the embedded-processes approach to memory, attention, and consciousness

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ARTICLE INFO

Keywords:
Wundt
Embedded processes
Working memory
Focus of attention
Activation
Long-term memory
Activated long-term memory
Introspection
History of psychology

ABSTRACT

Early research on memory was dominated by two researchers forging different paths: Hermann Ebbinghaus, interested in principles of learning and recall, and Wilhelm Wundt, founder of the first formal laboratory of experimental psychology, who was interested in empirical evidence to interpret conscious experience. Whereas the work of Ebbinghaus is a much-heralded precursor of modern research on long-term memory, the work of Wundt appears to be a mostly-forgotten precursor to research on working memory. We show how his scientific perspective is germane to more recent investigations, with emphasis on the embedded-processes approaches of Nelson Cowan and Klaus Oberauer, and how it is in contrast with most other recent theoretical approaches. This investigation is important because the embedded-process theorists, apparently like most modern researchers, have recognized few of Wundt's specific contributions. We explore commonalities between the approaches and suggest that an appreciation of these commonalities might enrich the field going forward.

1. Introduction

We tend to think of consciousness as only recently open to empirical investigation but the director of the first formal laboratory of experimental psychology, Wilhelm Wundt, discussed consciousness in a theoretical framework that seems remarkably similar to some modern concepts of working memory, the small amount of information temporarily accessible to consciousness. The modern work rarely has cited Wundt. In the domain of memory research, it is worth tracing what happened to the work of Wundt because it contains, as it were, important messages for us regarding our scientific attitude to the topic.

The topic of this paper may seem long overdue but, in important ways, it is timely. The voluminous work of Wundt has been difficult to obtain, and mostly not translated into English. Scientific historians have examined Wundt from multiple perspectives (for a good compendium see Rieber & Robinson, 2001) and there is at least one new reinterpretation of much of Wundt's work (Araujo, 2016). As Araujo documents at length, the views of Wundt himself changed from one in which unconscious inference played an important role in his view of the mind, to one in which only conscious aspects of the mind were deemed worthy of study. There are still disagreements between investigators; as just one example, Araujo states (p. 103) that "David Robinson (1987) speculates that the increasing popularization of the language of the unconscious in German philosophy led Wundt to abandon it, but he fails to offer convincing evidence for this."

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https://doi.org/10.1016/j.concog.2018.06.001
Received 10 February 2018; Received in revised form 23 May 2018; Accepted 1 June 2018

In some ways, we are far from the ideal investigators to wade into the controversy of the meaning of Wundt's work. We are not leading experts on the history of psychology, and we do not speak or read German fluently enough to try to read Wundt in original form. However, unlike the other investigators who have discussed Wundt, we are cognitive psychologists with a modern-day theoretical view that we think recaptured much of the spirit of Wundt's original enterprise (unbeknownst to Cowan until Rachev pointed it out). Given our new appreciation of Wundt's philosophical orientation and how thoughtful and penetrating his approach was, we see a possibly unique opportunity to explain how the field may now be positioned to benefit more from Wundt. For although Wundt has long been recognized as the originator of the first laboratory of experimental psychology, the historians seem to agree that the field went off in other directions and largely ignored or improperly simplified much of what Wundt had to say (as in the famous poem by Keith Douglas, *Simplify Me When I'm Dead*).

2. How the early field spawned modern approaches to memory

Today's memory research has been built primarily on the work of Ebbinghaus (1885/1913), who turned himself into a research participant to be tested on the acquisition of strings of nonsense syllables of various lengths after various retention intervals and various numbers of repetitions. Although he found a precursor of what we now term working memory in the "first fleeting grasp" of short lists that could be recalled immediately after only a single viewing, for the most part his forgetting curves served as the basis of a behaviorally-based science of learning and memory, which later flourished in the fields of verbal learning (e.g., Kausler, 1974) and then cognitive psychology (e.g., Crowder, 1976).

The modern field, however, is recognized not only as a science of behavior, in keeping with the approach of Ebbinghaus, but also as a science of the mind (e.g., Gardner, 1985). Wundt's work, while thoroughly empirical in nature, was carried out within a theoretical framework in which the subjective aspects of the mind were the objects of study, not just behaviors.

The focus on behavior versus conscious experience can lead to strikingly different graphic representations of memory processes. If the emphasis is primarily on behavior then the graphic representation that may seem most suitable is one in which there is a discrete progression from one process to the next, as in Sternberg's (1969) stimulus encoding, memory search, decision-making, and motor response processes or (stated in modern terminology) Broadbent's (1958) sensory memory, working memory, and long-term memory stores. Sometimes from a behavioral approach there is also recurrent entry into a process earlier in the stream after a later one is reached, as in the computer-flowchart-inspired representation of processing by Atkinson and Shiffrin (1968), or a model with multiple, separate but interacting components (e.g., Baddeley, 1986; Baddeley & Hitch, 1974; Logie, 2016). If, however, the emphasis is directly on the mind and consciousness, a better representation may be one that depicts processes more organically, as it were, with a limited focus of attention and awareness as central to other memorial processes and embedded in them, providing a flow of information from up to several sources in parallel into, and out of, this focus of attention.

The latter, experience-based graphic representation of processing is a fair description of the embedded-processes modeling framework of Cowan (1988; later elaborated upon by Cowan, 1999, 2005) and of the framework with an additional embedded layer described by Oberauer (2002). In Cowan's (1988) framework, the focus of attention can contain several well-integrated object representations at once and is embedded in a currently-activated portion of long-term memory. The latter can contain an unlimited number of separate feature representations, often not fully integrated into objects, subject to their mutual interference and decay; in turn, activated long-term memory is embedded within the wealth of knowledge of the individual, the memory system at large. Oberauer modified Cowan's focus of attention, calling it a capacity-limited region of direct access and proposing that the focus of attention is actually a mechanism embedded within this capacity-limited region, with the focus holding just a single item in a more privileged status.

The embedded-processes type of model has been popular among some brain researchers because it seems to mesh with assumptions based on brain research indicating that attention processes involved in working memory operate as a subsystem embedded within more general, sometimes autonomously-functioning information processing systems in the brain (e.g., Chein & Fiez, 2010; D'Esposito, & Postle, 2015; Ruchkin, Grafman, Cameron, & Berndt, 2003). Several articles on embedded-process approaches (Cowan, 1988, 1999, 2001, 2005; Oberauer, 2002), taken together, have been cited about 13,000 times.

Cowan (1988) attributed his model to the fusion of some important concepts underlying the embedded processes and their graphic representation. The most important precursors included (1) a proposal of some access to items outside of attention upon arrival of an important, related stimulus such as one's name, the attenuation theory (e.g., Treisman, 1964); (2) attentional orienting to information discrepant with the current neural model of the environment (Sokolov, 1963); and (3) the models of processing mentioned above (Atkinson & Shiffrin, 1968; Baddeley, 1986; Baddeley & Hitch, 1974; Broadbent, 1958). What Cowan was not aware of was a related precursor to his approach in the work of Wilhelm Wundt.

A depiction of the Wundt approach and that of Cowan (1988) appear for comparison in Fig. 1. Below, we elaborate on Wundt's approach to memory and then ask which aspects of it have been overlooked and might still be important to incorporate into modern approaches to the topics of attention and memory, and especially the embedded-processes approach.

3. Wundt's approach to memory, attention, and consciousness

Wundt's approach can be examined by starting with his model and then exploring the philosophical underpinnings of the approach leading to that model.

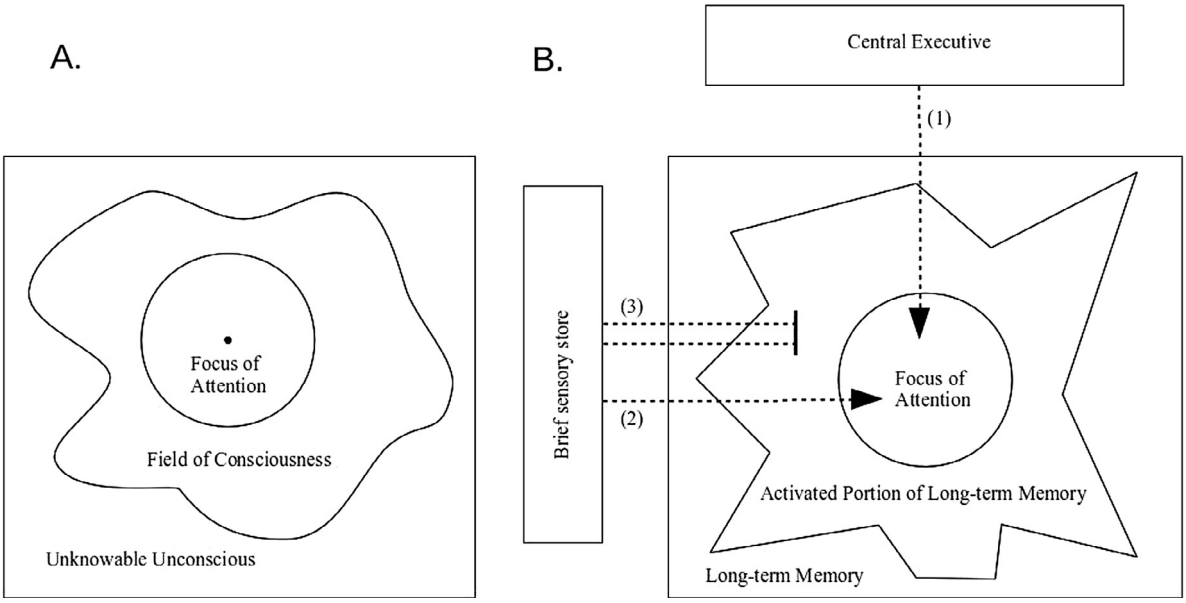

Fig. 1. A graphic depiction of two models of working memory and consciousness. A: Wundt's (1912) model of consciousness. In Wundt's model, the point in the center denotes the fixation point of consciousness. B: Cowan's (1988) embedded-processes model of working memory. Dashed arrows in Cowan's model represent (1) the direction of attention by the central executive and (2) orienting of attention when incoming information is discrepant with the current neural model of the environment. The two dashed lines ending in activated long-term memory (3) represent habituation of attentional orienting to unchanging stimuli.

3.1. Wundt's model of consciousness and memory

As stated by Blumenthal (1975), "[t]he basic premise in Wundtian psychology is that the only certain reality is immediate experience" (p. 1081). Thus, it is not surprising that Wundt put consciousness in the center of his scientific interests.

Wundt's theoretical views evolved throughout his career, as illustrated by the fact that one of his major works, the *Principles of Physiological Psychology* (Wundt, 1874/1903), was constantly revised and expanded (Hothersall, 1999, p. 101). Yet, a fairly stable and consistent picture of Wundt's model of consciousness is presented in three of his sources available in English (Wundt, 1892/1907, 1897, 1912). There, Wundt defined consciousness as "the interconnection which unites the elements to a single whole [that] always reaches beyond the individual compounds" (Wundt, 1897, p. 203). This definition highlights an integration function of consciousness that also has seemed important to modern theorists (e.g., Baars, 2002; Baars & Franklin, 2003; Cowan, 1988; Cowan, Donnell, & Saults, 2013). Wundt, however, in his later years thought of the unconscious as unknowable (e.g., Araujo, 2016; Carpenter, 2005, p. 65).

To represent consciousness, Wundt postulated a broad *field of consciousness*, defined as "the whole content of consciousness at any given moment" (Wundt, 1897, p. 207). Note that the elements within the field of consciousness did not have equal status, inasmuch as certain elements were perceived more clearly than others. In particular, the place for the element that is given in "the present moment" (Wundt, 1897, p. 210) and is "mostly clearly apprehended" (Wundt, 1912, p. 15) was designated as the *fixation point of consciousness*. The fixation point, however, is but the "ideal middle point of a central region, within which several impressions can be clearly and distinctly apprehended" (Wundt, 1912, pp. 15–16). Wundt called this central region around the fixation point the *focus of attention*.

Wundt (1897, 1912) emphasized the qualitative difference between the central area, or focus of attention, and the surrounding field of consciousness by highlighting two distinctive processes. *Apperception*, defined as "the elevation into the focus of attention" (Wundt, 1912, p. 35), is marked by clearness and distinctiveness, while *apprehension*, or "the entrance into the large region of consciousness" (Wundt, 1912, p. 35), designates more or less vague awareness of mental contents. Apperception, but not apprehension, is responsible for combining the elements within consciousness to form a coherent whole. As a result, material in the focus of attention is experienced as "brighter" and "cut off by a more or less clearly defined boundary line from the larger and darker field that surrounds it" (Wundt, 1912, p. 17).

Wundt was not the first to propose a two-level model of consciousness (Blumenthal, 1977) but he may have been the first to relate the hypothetical structure to experimental findings. In particular, the way Wundt defined the two regions of consciousness led him to the issue of measuring their capacity. Accordingly, one important question related to the capacity of the focus of attention, or *the scope of attention*, i.e. "the number of clear and distinct ideas present in consciousness" at a given moment (Wundt, 1892/1907, p. 243; cf. Cowan et al., 2005). To approach this question, Wundt presented subjects with a visual array of letters for a brief period of time (approximately 80 ms: Wundt, 1892/1907, p. 243) using a tachistoscope, and had them recall as many letters as they could. Experiments showed that, for relatively similar familiar stimuli, "four, or sometimes five, disconnected impressions (letters, numerals,

or lines of different direction) may be distinctly perceived" (Wundt, 1892/1907, p. 243). In the case of complex or unfamiliar stimuli, the number dropped to the range of one to three.

The second capacity-related question concerned the span of the field of consciousness, or *the scope of consciousness*, i.e. "the total amount of all the contents that can enter into consciousness at a given moment" (Wundt, 1897, p. 211). In a typical experiment, the subject was played two series of metronome beats in immediate succession and had to judge whether the series were same of different. The rationale was that the subject would not be able to perform this task successfully if the "preceding temporal series is not a unitary whole for consciousness, that is, when a part of its constituents have passed into unconsciousness before the end is reached" (Wundt, 1892/1907, p. 214). Wundt (1892/1907, 1912) observed that the scope of consciousness varied according to the length of the series and the tempo of the beats. In particular, performance was most effective when the interval between two strokes was 0.2–0.3 s. Wundt observed that, within this inter-beat interval, subjects spontaneously grouped the beat series by adding different levels of subjective accents to different beats (although the beats were objectively monotonous). Different groupings could lead to different estimates of the span of consciousness. In case of the simplest combinations, in 2/8 time, the estimate was 16 beats, or eight groups of two beats. In comparison, 4/4 time allowed more complex hierarchical grouping made by three levels of accents, which led to the formation of fewer groups (five) but of more complex contents (eight differently accentuated beats). Thus, in the optimal conditions, the field of consciousness could contain 5–8 complex ideas or 16–40 simple elements. Although some of the measurements that Wundt made could be viewed as arbitrary in that they depend on parameters that Wundt did not explicitly manipulate, the work is full of empirical questions that still seem vividly important and, in many cases, still unanswered today. It is way past time for a translation of his prolific work into English and a systematic re-examination of it.

3.2. The philosophical underpinnings of Wundt's approach

In his classic text, Boring (1957, pp. 328 ff.) described Wundt's approach with reference to some of his published work; today the most often-cited is his *Principles of Physiological Psychology* (Wundt, 1874/1903). Boring explained that Wundt believed in the exploration of consciousness as a main goal of his research, but did not believe that simple introspection was an adequate tool. He believed that, whereas physical effects have physical causes, psychological effects have psychological causes and should be investigated through those causes. For those chains of psychological cause-and-effect, he thought that behavioral testing could be of great use, but only for simple consciousness-including elements like the experience of duration, intensity, and color. For more complex phenomena, such as thinking about real events and complicated beliefs, emotions, and attitudes, he thought that the methods of the humanities rather than the sciences were all that was possible.

Wundt's philosophical views directly influenced his use of methodology. In particular, contrary to the popular view of him, Wundt denied the scientific merit of casual self-observation (Blumenthal, 1975, Danziger, 1980a). The method of introspection, or rather, "internal perception", "could yield acceptable data for science only insofar as experimental conditions permitted a replication of inner experience at will" (Danziger, 1980a, p. 247). In other words, scientific introspection should always go conjointly with experimentation. However, as Danziger (1980a) continues, "these conditions immediately imposed severe limitations on the scope of experimental psychology and of scientific introspection". In particular, certain areas such as sensation and perception, and, to a lesser degree, memory, imagery and attention, seemed suitable for introspection and experimentation, while others like thinking, emotions and social psychology did not (Danziger, 1980a).

Given this orientation, according to Boring (1957), Wundt was very interested in beginning the psychology of consciousness by, for example, examining the ability to compare two tones as a function of the time between them, to examine an instance of the fading of a conscious memory. He believed that for this kind of research goal, the participant had to be a full partner in the exploration. In other words, experimenter and participant were regarded as collaborators who could easily switch roles. This type of social interactions during psychological experimentation was in sharp contrast with another early psychological tradition, the experimental hypnosis tradition in France. The latter occurred in a medical setting and provides a closer precursor to the typical modern experimental setting, where the social roles of the experimenter and participants are mostly fixed, the former being the person in charge and the latter the source of data (Danziger, 1985). Notice that the currently-favored term of research "participant" seems more in keeping with Wundt's approach than does the formerly-standard term that has been pushed out of favor since the 1990s, that of research "subject."

By experimenting, Wundt was striving for a coherent hypothesis or model made from individual facts. Danziger (1980b, p. 113) quoted Wundt to say that "'The most accurate description of a field of phenomena leaves their coherence obscure as long as it does not lead to an explanatory hypothesis from which the individual facts can be derived' (Wundt, 1906, p. 206). Because for Wundt the explanation of the coherence of phenomena was the basic and essential task of all science, descriptive observation had to give way to experiment. By varying the conditions under which phenomena appear, the experimental method is able 'to proceed to the question of the why of phenomena.'"

Danziger (1980b, p. 116) went on to explain how introspection was worked into Wundt's psychological investigations: "To use a somewhat anachronistic modern terminology one might say that Wundt tended to draw on qualitative introspective material in the context of discovery and to rely on relatively objective methods in the context of verification. For instance, his tri-dimensional theory of feeling is introduced with the use of introspective illustrations but he attempted to verify it by means of objective measurements of affective response (Wundt, 1897). One may wonder whether his general approach in this respect was really so very different from that of some more modern psychologists, except that the latter have become shy about revealing the introspective context that germinated some of their hypotheses." Indeed, this kind of merging of subjective experience and objective measures has recently been rediscovered, as we will argue, as a promising avenue in research on consciousness and working memory.

The approach of Wundt depended on a notion of "voluntarism" (Blumenthal, 1975; Danziger, 1980b, pp. 117–119). Wundt was not so concerned with predicting and controlling behavior, but in understanding the logic of it, from a psychological point of view. An active participant engaged in acts of "apperception" or voluntary, attentive perception. The idea was that with the cooperation of the participant, well-controlled introspections can be converted into behavioral responses that reveal the logic of consciousness.

4. How the field left Wundt behind

There can be no doubt that much of the work of Wundt was repudiated, passed over, or abandoned (e.g., Carpenter, 2005). There are several practical reasons for this, including the modern tendency to consider the cognitive revolution as the starting point of work in the field; the disguise of Wundt's work on memory under the heading of conscious experience; and the relative rarity, to this day, of English translations of Wundt's prolific work, written in German.

There are other, more primary historical reasons why the field turned away from Wundt, well-described at length by Danziger (1990, chap. 3). In brief, Wundt saw his work as a branch of philosophy, hopefully enlightening that field by opening up a new avenue to the understanding of consciousness. His approach of experimentation was, however, seemingly oversimplified by his students (the most influential being Titchener in the United States and Külpe in Germany), who wanted to try a more direct type of introspection, training participants to say what they saw in basic terms. This approach was the grist for the mill of criticism by the behaviorists, led by J. B. Watson, because elaborate introspections varied so much among individuals and in that sense could not easily be replicated.

It is by now well acknowledged that the image of Wundt as introspectionist is a quite distorted one (Blumenthal, 1975, Danziger, 1980a; see previous section); studies relying exclusively on introspection were but a small fraction of his empirical work, which also included accuracy, reaction-time, and psychophysical measures (Hothersall, 1999, pp. 101–103). However, as we also saw, the very view of a highly restricted range of phenomena amenable to introspection went together with a quite limited view of application of the experimental method on studying psychological phenomena (Danziger, 1980a).

Moreover, Wundt had also set rather narrowly circumscribed goals for his method and others became interested in a plethora of more diverse, often practical psychological topics for which Wundt was unsure of the path of investigation (Danziger, 2001). For example, there was surely an interest in the potential of psychology as applied to education, medicine, child development, and social interactions. Given these new directions and criticisms of introspection, nuances of Wundt's approach appear to have been forgotten by most researchers after Wundt died.

5. Embers of Wundt in modern experimental psychology

We have found that few researchers in the field of cognitive psychology have cited Wundt even when his work is highly relevant. One notable exception is the seminal paper on the relation between sensory memory and working memory by Sperling (1960), which appears to have been inspired by a careful reading of Wundt. Sperling described experimentation in Wundt's laboratory that was a close precursor of his own methods, in which arrays of characters were briefly presented and followed by a post-array, partial report tone cue to help distinguish between a rich but short-lived sensory afterimage of the environment and a limited amount of information that could be transferred from sensory memory to what we now call working memory.

Although there has not been much subsequent discussion of Wundt's methods within empirical investigations in which these methods would be quite relevant, Blumenthal (1975, 1977) did review Wundt's contributions (see also the works of Danziger cited throughout this article and Leahey, 1979; Scheerer, 1980). These discussions, however, have left a mark in cognitive psychology that is extremely sparse and not well known, in contrast to, for example, the well-known contribution of Ebbinghaus to the field of memory.

6. Embedded processes in cognitive psychology compared to Wundt's framework

It is probably not an accident that Cowan (1988) decided on the embedded process representation of information processing around the same time that consciousness began to make a comeback in the field of cognitive psychology. For example, two seminal papers appeared in which it was shown that there is an effect of priming outside of conscious awareness (Marcel, 1983) but that episodic memory can be formed only with the assistance of conscious perception of the stimulus (Balota, 1983). Within a few years, there was an influential review of the role of consciousness in memory; implicit memory can form without consciousness, but consciousness-linked explicit memory (Schacter, 1987) has its own special function in governing voluntary behavior. It was within this zeitgeist that Cowan conceived of working memory as consisting of a conscious, coherent part (the focus of attention) embedded in a more autonomous part, the larger quantity of currently activated elements from long-term memory.

Cowan's (1988) review was intended to incorporate what was known about information processing into a framework that was true but left room for further detail when more was known. It can be viewed as a vindication of Wundt's approach that there are numerous similarities between Cowan's approach and the earlier approach of Wundt, which Cowan did not realize at the time. Our description of these similarities is intended to highlight the early advances of Wundt and to ponder how these advances might be further incorporated into today's work.

There are many similarities between the models of Wundt and Cowan, depicted in Fig. 1. Cowan (1988, 1995) drew upon a large body of evidence to propose a revised model of the information-processing system as an alternative for the then-dominant multistore model (Atkinson & Shiffrin, 1968). A prominent feature of the model is its embedded organization. Specifically, the memory system

consists of *long-term store*, a *short-term store* consisting of the subset of long-term memory that is currently *activated*, and a subset of the activated memory that can be directly accessed, that is, the *focus of attention*. The activated memory and the focus of attention have been conceived as the basic constituents of the working memory system, defined as "cognitive processes that retain information in an unusually accessible state, suitable for carrying out any task with a mental component" (Cowan, 1999, p. 62).

In Cowan's (1988) model, information within the focus of attention receives privileged processing, as compared to information that is merely in activated memory. In particular, the focus of attention is the area of special conscious awareness of several individual items or ideas. In it, processing is enhanced with an increased number and type of features encoded (including semantic features) and with the bound representations of features into objects and episodic representations of events available for explicit recall. Awareness in the focus of attention thus leads to a more coherent representation of the environment than is found outside of the focus. Another specific feature of the focus of attention is that it is capacity-limited, whereas the activated memory is time- and interference-limited. The access to the enhanced but limited processing within the focus of attention is controlled conjointly by voluntary processes, through a central executive, and involuntary processes, through orienting responses. Oberauer (2002) proposed a modification of Cowan's model by dividing the working memory space in three parts: the activated part of long-term memory, the region of direct access (corresponding to the focus of attention in Cowan's model) and a more narrow focus of attention holding one item only. The similarities between these frameworks and that of Wundt can be enumerated as follows.

6.1. Model organization

The embedded organization of both models imposes specific constraints on both models. It also helps explain findings that seem paradoxical if one assumes a linear flow of information, as in the traditional multistore information processing framework. For example, the embedded-processes model can account for the fact that unattended information can nevertheless be processed to some degree (Cherry, 1953); the model states that all information makes contact with long-term memory but that attention is automatically recruited only when the input is discrepant with the current neural model of the ongoing stimulation (as when there is an abrupt change in stimulation; cf. Sokolov, 1963). Thus, the embedded organization underlies the model's ways of explaining how attention interacts with memory.

6.2. The focus of attention in both models

The most striking part of the similarity of Wundt's conception to the embedded-process framework is that both of them defined a region of the focus of attention, where the stimuli receive enhanced processing, relative to a broader surrounding area. The similarity is not confined to the use of a common label but extends to crucial aspects such as capacity limits and the relationship with control process and awareness. There is a striking agreement between Cowan and Wundt as to the nature and the span of that limited capacity. Both Wundt (1892/1907, 1897, 1912) and Cowan (2001, 2010) defined that limit as being about four units.

Also, both models describe the narrower region of the focus of attention as the place for control processes. The emphasis on control processes was a prominent feature of Wundt's work (Blumenthal, 1975). He proposed that apperception, operating within the focus of attention, is responsible for the control processes of attention (Blumenthal, 1977; Christova, 1988). Similarly, in Cowan's model, the focus of attention is where executive control has its effect. The two models do diverge, however, as to the nature of the central control process itself. While the central executive is a separate component in Cowan's model, apperception is inherent to the focus of attention in Wundt's model.

Finally, both models relate the focus of attention to conscious information processing. Wundt's focus of attention was marked with a higher degree of awareness, compared to the broader field of consciousness. Similarly, though not identically, Cowan (1999) stated that the location of awareness at any given moment is within the focus of attention. In contrast, the activated information from long-term memory need not be consciously present, although it is in a highly available state temporarily and can easily be brought back into the focus of attention. The two models also converge in the conceived role of awareness in processing. For Wundt (1912), apperception is responsible for uniting and combining the elements into a coherent whole (p. 41). Similarly, for Cowan (1999), awareness leads to better analysis and hence more coherent representations than those outside the focus of attention.

6.3. Activated long-term memory and Wundt's field of consciousness

The broader areas that surround the focus of attention in the two models differ in some ways. However, considerable common ground can still be observed. One commonality concerns the function of the component, which is to hold the information in a highly-available state, beyond the limited capacity of the focus of attention. This function is essential for carrying out a mental task. For example, in sentence comprehension, "if the first word is totally forgotten by the time the second or third word is perceived, one is in bad shape" (Cowan, 1999, pp. 62–63). Similarly, Wundt (1912) observed that comprehending a sentence "is only possible as long as the preceding parts of the sentence from the last apperception remain in the field of consciousness" (pp 39–40).

In addition, both components have their limits. Wundt conceived of the field of consciousness as capacity-limited, but larger than the focus of attention. In contrast, Cowan's activated memory is time-limited, fading within about 10–20 s, and susceptible to interference from similar items (Cowan, 1999). Clearly, though, Wundt was also interested in loss of memory from consciousness over time, as in the tone study described by Boring (1957) and studies mentioned above measuring the scope of consciousness.

Wundt's reports of grouping in the field of consciousness point to another important aspect converging with the embedded-processes approach. The issue Wundt addressed could be described in modern terms as the rapid formation of complex,

hierarchically-arranged groups in immediate memory. Grouping improves the memory of materials and can be formed either on the basis of perceptually grouped input, as Wundt pointed out (cf. Cowan, Saults, Elliott, & Moreno, 2002), or on the basis of known combinations or "chunks" in the input, like the widely known acronyms in the letter series IBMUSA (cf. Miller, 1956). Hierarchical chunking, i.e., formation of chunks themselves composed of smaller chunks, can lead to a memory span of many times the usual seven or so (Chase, Ericsson, & Faloon, 1980). It is only recently that researchers have turned to asking about the role of new associations rapidly formed between items concurrently held as groups in working memory, either because of perceptual grouping or because the pattern in the stimuli allow for conceptual grouping and pattern detection (e.g., Brady & Tenenbaum, 2013; Chekaf, Cowan, & Mathy, 2016; Cowan et al., 2013). These ways of compressing the stimuli into larger units must be taken into account before the capacity of working memory can be assessed, as Wundt may already have understood.

Wundt's field of consciousness and Cowan's activated memory differ as to their level of conscious awareness. All material in the field of consciousness had to have some degree of consciousness, although not as clear and distinctive as that in the focus of attention. In contrast, the material in the activated memory of the embedded process model is not directly accessible to conscious processing, although it is in a highly available state. (Also, it may be that an entire scene giving rise to many activated elements of long-term memory can be represented in consciousness and the focus of attention as a single, holistic "item" along with a few individuated items in the focus.) Note also that "directly accessible" and "highly available" are close to one another as functional states, both being distinct from the material that is not currently activated. In that sense, Wundt's interpretation is still close to Cowan's, except for Wundt's assumption that there are degrees of consciousness, rather than Cowan's all-or-none interpretation.

6.4. A narrow focus of attention and Wundt's fixation point

Cowan's model has no direct analogue to Wundt's notion of a central fixation point within the focus of attention. However, Oberauer's (2002) extension of Cowan's model does, in the form of a one-item focus of attention within the capacity-limited region. Cowan (2005; cf. Cowan et al., 2005) did suggest, moreover, that it is possible for the focus of attention to zoom down to a single item when necessary, and Oberauer and Hein (2012) conversely suggested that it is possible for the focus of attention to zoom out to encompass more than one item when the task demands require that. In sum, then, there is commonality between Wundt's narrow focus of attention and rather comparable mechanisms within the embedded-processes approaches.

In his writings available to us, Wundt seems to have relied on phenomenological description to define the fixation point of consciousness, while Oberauer provided experimental support for his narrow focus and its role in processing. However, it is remarkable that a German researcher has proposed a model so close to that of another German researcher, made a century earlier; perhaps less remarkable knowing that Oberauer began his academic career as a philosopher.

Neither Cowan nor Oberauer seem to have been aware of Wundt's model. Rather, Cowan's model was based on a large body of new evidence that was not available to Wundt, and Oberauer elaborated on Cowan's ideas based on his own additional evidence. An overview of Cowan's main sources of inspiration showed that they have also omitted Wundt. As a result, two strikingly similar conceptions of human information processing have been created independently.

7. A world finally ready for Wundt's contribution?

7.1. Consciousness and cognition

It now seems clear that Wundt was correct in surmising that it was possible to use experimental techniques to harness to some good effect the phenomenon of consciousness. Since 2001 the field has had the journal *Consciousness and Cognition*. Consciousness has been recently brought back at the spotlight of cognitive psychology, as a "legitimate and tractable scientific problem" (Baddeley, 2007). In particular, it plays an important role in prominent models of working memory (e.g. Baddeley, 1986, 2007, Cowan, 1988, 1995), the mechanisms that retain a limited amount of information temporarily in an accessible state in memory, which can be used for the completion of cognitive tasks. However, authors of working memory models have been generally slow at explicitly including discussions of the role of consciousness. As Miyake and Shah (1999) point out, beyond the general agreement that working memory and consciousness are interconnected, there is little agreement across theories as to the nature of the relationship.

Baddeley (1992) pointed out two reasons why he had been reluctant to elaborate on the concept of consciousness in his study of working memory. One is that his working memory model was not originally developed to deal with issues of consciousness. Up to a certain point, explicitly mentioning consciousness would thus be an unnecessary complication. The other reason is historical. The study of consciousness has been traditionally associated with early introspective studies. The failure of this approach made Baddeley reluctant to address consciousness until two decades after his original model. This rationale might well have been shared by others, too. Currently, however, there is a resurgence of interest in topics related to consciousness. For example, many researchers recently have been carrying out research on the effects of prioritization of information in working memory, placing some information in the focus of attention at the expense of other information (e.g., Cowan, Saults, & Blume, 2014; Griffin & Nobre, 2003; Hu, Allen, Baddeley, & Hitch, 2016; Morey & Bieler, 2013; Souza & Oberauer, 2017).

7.2. Introspection and cognition

It also now seems clear that Wundt was a bit too pessimistic in narrowly circumscribing the situations for which an experimental exploration of consciousness could be usefully applied; the practical advantages of that approach were not clear to him, probably

because of the paucity of available evidence.

Recent studies have made it very clear that the attention-based component of working memory is a close correlate of all sorts of cognitive aptitudes (Cowan et al., 2005; Kane et al., 2004; Unsworth & Engle, 2007) that are of practical importance in education and the workplace (Cowan, 2014; Wilhelm & Engle, 2005). Moreover, a common type of developmental disorder is attention deficit disorder. Investigations of the relation of attention to working memory have relied on mnemonic reports of having become conscious of an item presented in a field to be ignored, one's name; this research has shown that young adults with low working memory span often notice their names in a channel to be ignored, presumably because they do not have tight control of attention (Conway, Cowan, & Bunting, 2001). This finding is not a tautology, inasmuch as older adults who have working memory performance comparable to the low-span young adults show a different pattern, very rarely noticing their names in the unattended channel (Naveh-Benjamin et al., 2014).

The procedures now used to examine the control of attention in everyday life include a heavier reliance on introspection. For example, Kane et al. (2007) used mobile devices to allow participants to be probed at various times during the day to answer questions about whether their minds were wandering; unintended mind-wandering was correlated with low working memory test performance.

Whereas Wundt saw the appropriate level of explanation for psychological effects to be psychological causes, there is currently less of an imperative to avoid mixing psychological and physical levels of analysis. Killeen (2001) summarized from Aristotle four types of causal explanation, "efficient causes (triggers), formal causes (models), material causes (substrates or mechanisms), and final causes (functions)" (p. 136). The efficient cause of a psychological effect such as remembering an item is likely to be a constellation of psychological causes (e.g., encoding of the appropriate retrieval cues), and a formal cause may consist of some weighting or interaction of these psychological causes to form a mathematical model of the process. However, physiological underpinnings now can be taken into account to form a material cause of the psychological effect, as Wundt would presumably have wanted.

Modern cognitive psychology seems to be in a particularly favorable position to profit from the merging of subjective experience and objective data advocated by Wundt (Danziger, 1980a, 1980b; see Section 3.2). As Cowan (2012) argued, the advances in the ease of using computers to study vision and then audition put more recent research in a much better position relative to pioneering research even within the modern cognitive era. Technical advancements, then, can also help solve most of the difficulties Wundt faced in trying to keep up with his precision standards (as described by Benschop & Draaisma, 2000), while, at the same time, pushing Wundt's approach further on.

Robinson's (2001) description of Wundt's program of reaction time experiments shows how Wundt's approach differed from the typical modern-day experiments. In modern experiments, the typical sequence of events is that the participant receives a stimulus, makes some decision about the stimulus, and reports on that decision. Although Wundt did plenty of those experiments, in later experiments he often had individuals receive a stimulus, attend to an internal state of consciousness, and report something based on that internal state. For example, in his work with his assistant Ludwig Lange, participants were asked to pay special attention either to the sensations to which they were to respond or to the muscular movements that they were about to make, the latter shortening the reaction times (presumably by allowing earlier formulation of the response while evaluation of the stimulus was ongoing). One may sense the difficulty of trying to report on otherwise unobservable internal processes in order to improve our understanding of consciousness, but this method has made a recent comeback in cognitive neuroscience, along the lines of Wundt's approach. As one interesting example, in research on binocular rivalry, two stimuli are concurrently presented to different eyes but, if the stimuli cannot be fused into a single coherent image, one stimulus dominates and is seen (e.g., green horizontal stripes) while the other stimulus is suppressed and unseen (e.g., red vertical stripes). The situation is fluid in that, in a matter of seconds, the percept tends to switch from one stimulus being perceived to that one being suppressed and the other one now being perceived instead. That is, the dominant percept can shift back and forth. Moreover, brain areas can be found that differ in activation depending on which stimulus is currently perceived. Zaretskaya, Thielscher, Logothetis, and Bartels (2010) were able to take this approach further, finding that transcranial magnetic stimulation to an area that is active during reported switches of perception prolonged the amount of time during which one percept was seen before a reported switch to the other percept.

Recently, the role of attention within an embedded-processes framework has become clearer in neuroimaging signals corresponding specifically to items that are not just in working memory, but also in the current focus of attention (Lewis-Peacock, Drysdale, Oberauer, & Postle, 2012; Rose et al., 2016) or that are retained with an abstract level of representation that includes both visual and verbal items, and therefore is likely to reflect information in the focus of attention (Chein & Fiez, 2010; Chein, Moore, & Conway, 2011; Cowan et al., 2011; Majerus et al., 2016). Other neural mechanisms are involved in the control of attention (e.g., Gray, Chabris, & Braver, 2003; Majerus, Péters, Bouffier, Cowan, & Phillips, 2017). Summarizing across studies, it seems clear that the frontal-parietal network controls attention, with an index of the currently-held items apparent in parietal areas (in particular, in part of the intraparietal sulcus). A representation of the actual information that is included in working memory apparently is represented in posterior cortical areas that did the encoding of the information in the first place. Together, these posterior responses along with frontal-parietal involvement (as the attention-based contribution) make up what is probably a key portion of the conscious representation of events.

Although modern investigations to some extent obviously stand on their own, for the maximal application of new neuroscientific tools it is helpful to be aware of which philosophical questions were just out of reach for Wundt and now may be within reach. There is a new potential for the convergence of deliberate reports of conscious mental states and neuroimaging documentation of physical events related to those mental states. For example, the intraparietal sulcus areas that are more active when more items are in working memory (Cowan et al., 2011; Majerus et al., 2016; Todd & Marois, 2004) also form the hub of a network with areas that represent the attended information in working memory (Lewis-Peacock et al., 2012; Li, Christ, & Cowan, 2014; Palva, Monto, Kulashekhar, &

Palva, 2010); also form the hub of a related network for attention to the external environment (Anderson, Ferguson, Lopez-Larson, & Yurgelun-Todd, 2010; Silk, Bellgrove, Wrafter, Mattingley, & Cunnington, 2010); and also include an area that alters the duration of dominance in binocular rivalry when transcranial magnetic stimulation is applied (Zaretskaya et al., 2010), namely part of the right intraparietal sulcus. By asking more refined questions about mental states while measuring brain reactions, we might learn the substrate of Wundt's field of consciousness (the posterior brain activity representing stimulus information?), focus of attention (activity in the intraparietal sulcus?) and fixation point of attention (some especially privileged portion of this network?).

In sum, the behavioral and neuroimaging aspects of these investigations have been versatile, but the field could now learn from Wundt that it would be helpful to be more versatile also in terms of varying the instructions to participants in these studies, to pinpoint more specific mental states and their neural substrates. As another example of this need, there has been much work on what the brain does when the participant is given no overt task, termed resting-state activity or the Default Mode Network (Raichle et al., 2001), but more work is needed to determine the mental states that give rise to this network. For example, is the participant just relaxing or for obtaining the typical neural pattern is it important that the participant is, say, daydreaming, wondering what events will come next, or perhaps concentrating hard to obey the instructions not to move in the MRI machine? It seems, then, that having inherited the pursuit of precision of the early experimental psychology, modern cognitive science is also better technologically equipped to profit from the merging of objective and subjective measures, provided that the importance of such an approach is recognized.

8. Conclusions

Although it seems like an implausible tale, the field of experimental psychology has touted the originator of the first formal laboratory of experimental psychology, Wilhelm Wundt, without really integrating into the field the many important contributions that he made. Here we have identified Wundt's view on consciousness and memory as a close precursor to the embedded-processes views of processing and memory (Cowan, 1988; Oberauer, 2002). Wundt's empirical and theoretical contributions have been overlooked by most researchers, including Cowan and Oberauer. Limitations of Wundt's work include (1) restrictions that he placed on the domain of experimental investigation that he thought to be suitable to make use of introspective judgments, and (2) a somewhat artificial separation that he placed between the theoretical psychology of the mind and the more practical psychology of behavior. With hindsight, readers of Wundt and present-day psychologists would appear to have a great deal that they can learn from one another.

Acknowledgments

We thank the New Bulgarian University's 23rd International Summer School in Cognitive Science, held in 2016, for providing the opportunity that inspired this research. We thank Arthur Blumenthal for helpful comments. We are grateful to Prof. Evdokia Christova-Slavcheva, whose paper and lectures informed N.R.R. and thereby inspired the question that triggered our collaboration. The research was supported by NIH Grant R01-HD21338 to Cowan.

Supplementary material

There are no supplementary materials associated with this article.

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