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capacity limits and consciousness Capacity limits refer to limits in how much information an individual can process at one time.

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1. A brief history

Early in the history of experimental psychology, it was suggested that capacity limits are related to the limits of conscious awareness. For example, James (1890) described limits in how much information can be attended at once, in a chapter on *attention; and he described limits in how much information can be held in mind at once, in a chapter on *memory. In the latter chapter, he distinguished between *primary memory*, the trailing edge of the conscious present comprising the small amount of information recently experienced and still held in mind; and *secondary memory*, the vast amount of information that one can recollect from previous experiences, most of which is not in conscious awareness at any one time. Experimental work supporting these concepts was already available to James from contemporary researchers, including Wilhelm Wundt, who founded the first experimental psychology laboratory. In modern terms, primary and secondary memory are similar to **working memory* and *long-term memory* although, according to most investigators, working memory is a collection of abilities used to maintain information for ongoing tasks and only part of it is associated with consciousness.

In the late 1950s and early 1960s, the concepts of capacity limits began to receive further clarification with the birth of the discipline known as *cognitive psychology*. Broadbent (1958) in a seminal book described some work from investigators of the period indicating tight limits on attention. For example, individuals who received different spoken messages in both ears at the same time were unable to listen fully to more than one of these messages at a particular moment. Miller (1956) described work indicating limits on how long a list has to be before people can no longer repeat it back. This occurs in adults for lists longer than 5–9 items, with the manageable list length within that range depending on the materials and the individuals involved. One of the most important questions we must address is how attention and primary memory limits are related to one another. Are they different and, if so, which one indicates how much information is in conscious awareness? This will be discussed.

2. Objective and subjective sources of evidence of capacity limits and consciousness

Philosophers worry about a distinction between *objective* sources of information used to study capacity limits, and *subjective* sources of information used to understand consciousness. For objective information, one gives directions to research participants and then collects and analyses their responses to particular types of stimuli, made according to those directions. The only kind of subjective information is one's own experience of what it is like to be conscious (aware) of various things or ideas. People usually agree that it is not possible to be conscious of a large number of things at once, so it makes sense to hypothesize that the limits on consciousness and the limits on information processing have the same causes. However, logically speaking, this need not be the case.

Certain experimental methods serve as our bridge between subjective and objective sources of information. If an experimental participant claims to be conscious of something, we generally give credit for the individual being conscious of it. Often, we verify this by having the participant describe the information. For example, it is not considered good methodology to ask an individual, 'Did you hear that tone?' One could believe one is aware of a tone without really hearing the intended tone. It is considered better methodology to ask, 'Do you think a tone was presented?' On some trials, no tone is presented and one can compare the proportion of 'yes' responses on tone-present and tone-absent trials. Nevertheless, an individual could be conscious of some information but could still say 'no', depending on how incomplete information is interpreted.

3. Capacity limits, type 1: information processing, attention, and consciousness

There seem to be solid demonstrations that individuals can process some information outside the focus of attention and, presumably, outside conscious awareness. One demonstration is found, for example, in early work on selective listening (Broadbent 1958). Only one message could be comprehended at once but a change in the speaker's voice within the unattended message (say, from a male to a female speaker) automatically recruited attention away from the attended message and to the formerly unattended one. The evidence was obtained by requiring that the attended message be repeated. In that type of task, breaks in repetition typically are found to occur right after the voice changes in the unattended message, and participants in that situation often note the change or react to it and can remember it.

There has been less agreement about whether higher-level semantic information can be processed outside attention. Moray (1959) found that people sometimes noticed their own name when it was included in the unattended message, implying that the name had to have been identified before it was attended. However, one important question is whether the individuals who noticed actually were focusing their attention steadily on the message that they were supposed to repeat. When Conway et al. (2001) examined this for individuals in the highest and the lowest quartiles of ability on a working memory span task (termed high- and low-span, respectively), they found that only 20% of the high-span individuals noticed their names, whereas 65% of the low-span individuals noticed their names. This outcome suggests that the low-span individuals may have noticed their names only because their attention often wandered away from the assigned message, or was not as strongly focused on it as in the case of high-span individuals, making attention available for the supposedly unattended message. This tends to negate the idea that one's name can be automatically processed without attention, in which case high-span individuals would be expected to notice their names more often than low-span individuals.

There are some clear cases of processing without consciousness. In *blindsight, a particular effect of one kind of brain damage, an individual claims to be unable to see one portion of the visual field but still accurately points to the location of an object in that field, if required to do so (even though such patients often find the request illogical). Processing without consciousness of the processed object seems to occur.

In normal individuals, one can find *priming effects in which one stimulus influences the interpretation of another one, without awareness of the primed stimulus. This occurs, for example, if a priming word is presented with a very short interval before a masking pattern is presented, and is followed by a target word that the participant must identify, such as the word 'dog'. This target word can be identified more quickly if the preceding priming word is semantically related (e.g. 'cat') than if it is unrelated (e.g. 'brick'), even on trials in which the participant denies having seen the priming word at all and later shows no memory of it.

The question arises as to how much can be processed not only without conscious awareness, but also without attention. In the above cases, participants attended to the location of the stimulus in question, even when they remained unaware of the stimulus itself. As in the early work using selective listening procedures, work on vision by Ann Treisman and others has suggested that individuals can process simple physical features automatically, whereas attention is needed to process combinations of those features. This has been investigated by presenting arrays in which participants had to find a specific target item (e.g. a red square) among other, distracting items with a common feature distinguishing them from the target (e.g. all red circles, or all green squares) or among distracting items that shared multiple features with the target (e.g. some red circles and some green squares on the same trial). In the former case (a common distinguishing feature), searching for the target is rapid no matter how many distracting objects are included in the array. This suggests that participants can abstract physical features from many objects at once, and that an item with a unique feature automatically stands out (e.g. the only square or the only red item in the array). However, when the target can be distinguished from the distracting objects only by the particular conjunction of features (e.g. the only red square), searching for the target occurs slowly and depends on how many distracting objects are present. Thus, it takes focused attention, and presumably conscious awareness, to find an object with a particular conjunction of features. This attention must be applied relatively slowly, to just one object or a small number of objects at a time. Further research along these lines (Chong and Treisman 2005) suggests that it is possible for the brain automatically to compute statistical averages of features, such as the mean size of a circle in an array of circles of various sizes.

An especially interesting procedure that illustrates a limit on attention and awareness is *change blindness. If one views a scene and it cuts to another scene, something in the scene can change and, often, people will not notice the change. For example, in a scene of a table setting, square napkins might be replaced with triangular napkins without people noticing. This appears to occur because only a small number of objects

can be attended at once and unattended objects are processed to a level that allows the entire scene to be perceived and comprehended in some holistic sense, but not to a level that allows individual details of most objects to be registered in memory.

4. Capacity limits, type 2: working memory, primary memory, and consciousness

The previous discussion implies that attention is closely related to conscious awareness (although for differences between the two see ATTENTION AND AWAREDNESS). Next, consider the other main faculty of the mind that may be linked to consciousness, namely primary memory. Here, the case may not be as straightforward as one would think. Miller (1956) showed that people can repeat lists of about seven items, but are they conscious of all seven at once? Not necessarily. Miller also showed that people can improve performance by grouping items together to form larger units called *chunks*. For example, it may be much more difficult to remember a list of nine random letters than it is to remember the nine letters *IRS–FBI–CIA*, because one may recognize acronyms for three prominent United States agencies in the latter case and therefore may have to keep in mind only three chunks. Once the grouping has occurred, however, it is not clear if one is simultaneously aware of all of the original elements in the set, in this example including *I, R, S, F, B, C*, and *A*. Miller did not specifically consider that the seven random items that a person might remember could be memorable only because new, multi-item chunks are formed on the spot. For example, if one remembers the telephone number *548-8634*, one might have accomplished that by quickly memorizing the digit groups *548*, *86*, and *34*. After that there might be simultaneous awareness of the three chunks of information, but not necessarily of the individual digits within each chunk.

People have a large number of strategies and resources at their disposal to remember word lists and other stimuli, and these strategies and resources together make up working memory. For example, they may recite the words silently to themselves, and this covert rehearsal process may take attention only for its initiation (Baddeley 1986). Rehearsal might have to be prevented before one can fairly measure the conscious part of working memory capacity (i.e. the primary memory of William James). The chunking process also may have to be controlled so that one knows how many items or chunks are being held. A large number of studies appearing to meet those requirements seem to suggest that most adults can retain 3–5 items at once (Cowan 2005). This is the limit, for example, in a type of method in which an array of coloured squares is briefly presented, followed after a short delay by a second array identical to the first or differing in the colour of one square, to be compared to the first array (Luck and Vogel 1997). A similar limit of 3–5 items occurs for verbal lists when one prevents effective rehearsal and grouping by presenting items rapidly with an unpredictable ending point of the list, or when one requires that a single word or syllable be repeated over and over during presentation of the list in order to suppress rehearsal.

What is essential in such procedures is that the research participant has insufficient time to group items together to form larger, multi-item chunks (Cowan 2001). Another successful technique is to test free recall of lists of multi-item chunks that have a known size because they were taught in a training session before the recall task. Chen and Cowan (2005) did that with learned pairs and singletons, and obtained similar results (3–5 chunks recalled).

A limit in primary memory of 3–5 items seems to be analogous to the limits in attention and conscious awareness. The latter are assumed to be general in that attention to, and conscious awareness of, stimuli in one domain detracts from attention and awareness in another domain. For example, listening intently to music would not be a good idea while one is working as an air traffic controller because attention would sometimes be withdrawn from details of the air traffic display to listen to parts of the music. Similarly, in the case of primary memory, Morey and Cowan (2004) found that reciting a random seven-digit list detracted from carrying out the two-array comparison procedure of Luck and Vogel that has just been described, whereas reciting a known seven-digit number (the participant's telephone number) had little effect.

It is not clear where the 3–5-chunk working memory capacity limit comes from, or how it may help the human species to survive. Cowan (2001, 2005) summarized various authors' speculations on these matters. The capacity limit may occur because each object or chunk in working memory is represented by the concurrent firing of neurons signalling various features of that object. Neural circuits for all objects represented in working memory must be activated in turn within a limited period and, if too many objects are included, there may be contamination between the different circuits representing two or more objects. Capacity limits may be beneficial in highlighting the most important information to guide actions in the right direction; representation of too much at once might result in actions that were based on confusions or were dangerously slow in emergency situations. Some mathematical analyses suggest that forming chunks of 3–5 items allows optimal searching for the items. To acquire complex tasks and skills, chunking can be applied in a reiterative fashion to encompass, in principle, any amount of information.

5. Reconciling limits in attention, primary memory, and consciousness

A major question that remains is how to reconcile the different capacity limits of attention vs primary memory. People generally can attend to only one message at a time, whereas they can keep several items at once in primary memory. Can these somehow represent compatible limits on conscious awareness? Perhaps so. There are several possible resolutions of the findings with attention vs primary memory. It might be that only a single message can be attended and understood because several ideas in the message must be held in primary memory at once, long enough for them to be integrated into a coherent message. Alternatively, the several (3–5) ideas that can be held in primary memory at once may have to be sufficiently uniform in type to be integrated into a coherent scene, in effect becoming like one message. According to this account, one would have difficulty remembering, say, one tone, one colour, one letter, and one shape at the same time because an integration of these events may not be easy to form. The more severe limit for paying attention, compared to the primary memory limit, might also occur because the items to be attended are fleeting, whereas items to be held in working memory theoretically might be entered into attention one at a time, or at least at a limited rate, and must be made available long enough for that to happen (Cowan 2005).

We at least know that individuals who can hold more items in primary memory seem to be many of the same individuals who are capable of carrying out difficult attention tasks. Two such tasks are (1) to go against what comes naturally by looking in the direction opposite to where an object has suddenly appeared, called *anti-saccade eye movements* (Kane et al. 2004); and (2) efficiently to filter out irrelevant objects so that only the relevant ones have to be retained in working memory (e.g. Conway et al. 2001). However, one study suggests that the capacity of primary memory and the ability to control attention are less than perfectly correlated across individuals (Cowan et al. 2006), and that both of these traits independently contribute to intelligence. It may be that the focus of attention and conscious awareness need to be flexible, expanding to apprehend a field of objects or contracting to focus intensively on a difficult task such as making an anti-saccade movement. If so, attention and primary memory tasks should interfere with one another to some extent, and this seems to be the case (Bunting et al. in press). There may also be additional skills that help primary memory but not attention, or vice versa. The present field of study of memory and attention and their relation to conscious awareness is exciting, but there is much left to learn.

See also AUTOMATICITY; GLOBAL WORKSPACE THEORY

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Cartesian dualism See DUALISM

cerebellum See BRAIN

change blindness Change blindness, a term coined by Ronald Rensink and colleagues (Rensink et al. 1997), refers to the striking difficulty people have in noticing large changes to scenes or objects. When a change is