Wilhelm Wundt

CHAPTER 3.2

Mental Chronometry

Human reaction time can be impressively fast under optimal conditions. For example world class sprinters at the 2008 Beijing Olympics sometimes had reaction times (RTs) to the starter's pistol that were as quick as 110 milliseconds (*110 ms* is just a bit more than 1/10th of a second). A false start is defined by the International Association of Athletics Federations (IAAF) as a reaction time (in this context, a leg movement detected by electronic sensors time-locked to the starter's signal) that is shorter than or equal to 100 ms. This value was decided on because objective tests have shown that no one, however much he or she practices, can produce a voluntary RT that is equal to or faster than 100 ms from the onset (the beginning) of a sensory event like a tone or a flash of light.

Any task, even one that simply demands a prepared action to a cue (for example, an athlete beginning to move as quickly as possible on the starter's signal), takes a certain duration that reflects the time course of underlying mental events. From a methodological standpoint, the average RT will tell us nothing about the processing steps involved in a particular task. The athlete is in some preparatory state that will rapidly trigger a particular course of action as soon as the brain decodes a go signal but beyond this very general description, we do not have more to say, other than that the whole process from the onset of the the auditory signal to the beginning of the motor response can be as fast as (but not much faster than) 110 ms.

We need some way of using RT (the time interval in milliseconds from the onset of a particular sensory event to a response) to identify the structure and organization of mental events. This enterprise, which began under Wundt's influence, is referred to as *mental chronometry*. Nowadays one can read articles or books with titles like *Timing the Brain: Mental Chronometry as a Tool in Neuroscience*, or *Chronometric Explorations of Mind*. The use of RT to test claims about cognitive processing systems is a crucial part of modern experimental psychology.

Donders' Subtractive Method

The original attempts by Wundt and his students were, perhaps not surprisingly, limited in important ways. It is by understanding and going beyond these limitations that mental chronometry has become so fundamental to modern psychology. F.C. Donders, a medical scientist and ophthalmologist working with Wundt, developed an approach in 1868 which is referred to as the *subtractive method*. The idea is to design a number of tasks in such a way that each task adds a different processing stage which can then by isolated by subtraction the average RT of one task from another.

Consider the example with which we began this section. Preparing a response to a stimulus or go signal (if you are a sprinter in a race, you prepare to leap forward when you hear the starter's signal) is pretty much the simplest voluntary task it is possible to devise. You know exactly what you have to do before the event that triggers the action, and the event itself is just a stimulus to which you must react; the task does not require that you distinguish between different sensory events (say, a loud versus a softer start signal) before reaching a decision to move.

Donders termed this kind of reaction, a *simple* reaction; there is only one response to a single stimulus. For example, a light goes on and the instruction is to press a key or a button as soon as possible after the onset of the stimulus. For Donders, this simple RT task (we will call it Task A) could be used as a *baseline*. Task A (requiring only simple reactions) captures the overall speed of responding to a predetermined event. Included in the task is the translation of a motor intention into an overt physical action, so we will refer to this component as *response execution*. Donders assumed that the task was sensitive to factors like the average speed of nerve conduction in each individual. We can compare the RT we obtain in this task with another more complex task (call this Task B) that requires additional processing steps. Subtracting the average RT's obtained for the two tasks (Task B - Task A) should give you an RT difference which according to Donders' subtractive methodology, would then provide a pure measure of the time required to complete these additional processing steps.

Suppose in Task B there is more than just one stimulus and a single response. Instead, let us require the following of our participants: If the stimulus is a triangle, press one button or response key as quickly as possible (say, a button beneath the forefinger of your right hand). If the stimulus is a circle, press another button (a button beneath the forefinger finger of your left hand).

Task B involves a *choice* reaction. You must *identify* which shape (triangle or circle) has been presented, and you must *select* which key (left or right) to depress. A choice reaction task therefore requires the mental operations of *stimulus identification* and *response selection* as well as response execution.

Consider now Task C designed by Donders. The task requires only one response linked to a stimulus (say, respond to the triangle, and ignore the circle). Like Task B, you must identify which of two stimuli has been presented (triangle versus circle). There is no requirement however to *choose between two alternative responses* once you have detected the target event. Task C is referred to in the modern literature as a *go/nogo*

task. The C reaction involves *stimulus identification, and response execution*, according to Donders, but *no* response selection.

We can subtract Tasks A, B and C as follows:

The average RT for Task C *minus* the average RT for Task A (*C-A*) will provide us with a measure of how long stimulus identification takes.

Task B minus Task C *(B-C)* should indicate the time for response selection.

Despite its intuitive appeal, the logic of Donder's subtraction methodology is not at all straightforward. It rests on three assumptions:

(i) The mental processes of stimulus detection, stimulus identification, response selection and response execution are arranged sequentially in the sense that the output of one serves as the input to the next.

(ii) Only one process can be active at a given instant between stimulus input and response output. Each process or processing stage takes a certain amount of time, referred to as the *stage duration*. RT is equal to the sum of all the stage durations (*the serial processing assumption*).

(iii) A stage can be added or omitted to a sequence of processes without altering the duration of the other processing stages. This is termed the *assumption of pure insertion.*

The first two assumptions may be valid under certain task conditions but are unlikely to be true of cognitive processes in general. For example, in *cascade* models, later stages of information processing can begin to operate before previous stages reach completion. Each stage begin working on partial information that rapidly becomes more detailed over time, until enough information has accumulated in the system to trigger a response.

The most contentious assumption, however, is the assumption of pure insertion, that a stage of processing can be added to a sequence without changing the operation of previous processing stages. Students of Wundt relied on introspection to argue that performing Task C (go/nogo) did not feel like carrying out Task A with just the added component of stimulus identification. The task itself felt like something qualitatively different. Likewise, it was argued on the basis of introspection that Task B did not feel like Task C with the addition of an extra component. All the tasks *felt* quite different in ways that did not support the assumption of pure insertion.

You should raise your eyebrows, of course, at this kind of argument. The emphasis on introspection as an analytic tool to uncover the organization of basic cognitive processes, is no longer a fundamental part of modern psychology. There are good reasons for this; much of the processing that underlies speeded reaction time tasks is unconscious, so no amount of training in introspective techniques can grant us reliable access to mental events that unfold within a few hundred milliseconds.

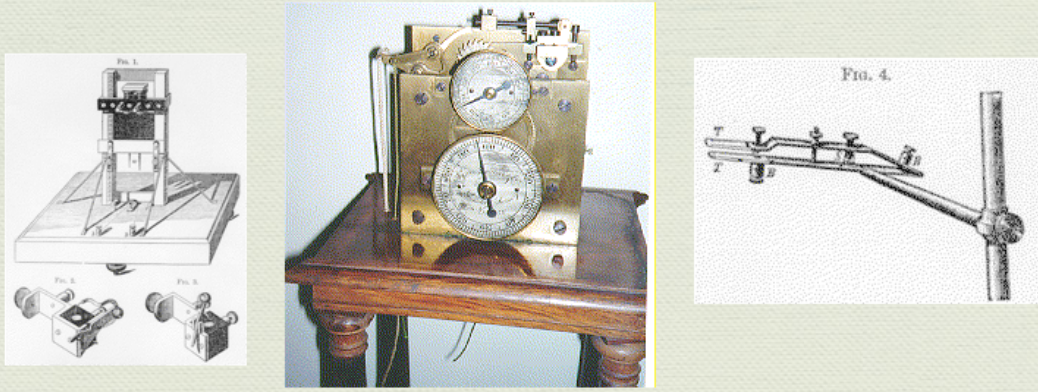
How would we develop an adequate test of the validity of the assumption of pure insertion, at least in regard to Donders' A, B and C tasks? Donders himself expressed some concern about this assumption. He wrote:

Some people give the response (in Task C) when they should have remained silent. And if this happens once, the whole series must be rejected: for, how can we be sure that when they had to make the response and did make it, they had properly waited until they should have discriminated?

Take some time to think about the concern that Donders' expressed (it's a good idea to read the segment above more than once). Suppose participants on the go/nogo task incorrectly respond to the *nogo* stimulus (in our example the circle) on a certain percentage of trials, which they have been instructed to ignore. These errors (a rapid anticipatory response triggered incorrectly by the wrong stimulus) might also have occurred for the target object (the square or the *go signal*), only the experimenter would have to count these as *correct* and has no way of distinguishing between these responses and other RT's that involved more detailed processing of the target square. In other words, the participant may have changed the amount of time he or she allows before responding to the target in the go/nogo task, triggering on some trials very fast anticipatory responses before the stage of identification has been completed. If this were true, the components involved in Task C are not just those which determine performance in Task B minus the added stage of response selection. The go/nogo task may differ from the choice task in other respects as well, either at the level of *stimulus identification* or at the stage of *response execution* (indexed by the component labelled 'baseline'). Case Study 13 describes a modern attempt to evaluate Donders' claim that Task C (go/nogo) differs from Task B only in regard to the process of *response selection*. Unfortunately, you will see the evidence suggests that this assumption is almost certainly incorrect.

Pure insertion revisited

Case Study 13



The image on the left depicts Cattell's device for presenting a visual display to an observer. In the middle is the chronoscope and on the right the voice-activated device which is triggered by a spoken response. The vibration of the sound moved thin metal plates to generate an electronic signal which then stopped the chronoscope, providing a measure of the response time in milliseconds from the onset of the stimulus.

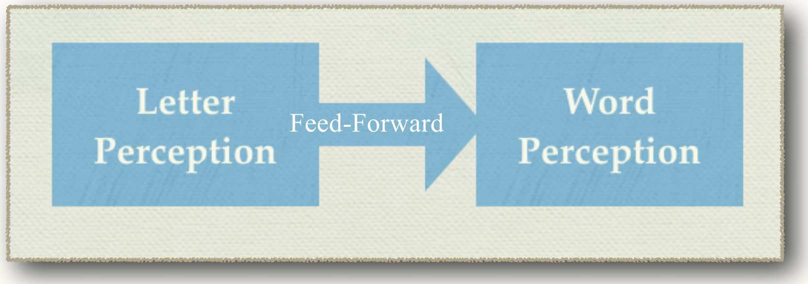
Interactive Activation

In the late 19th century, James McKeen Cattell -- a student of Wundt who went on to hold a professorship at Cornell University -- invented equipment that allowed him to measure the speed with which an observer could identify a visual word, letter or other object. The stimulus on each trial (a printed card) was hidden behind a black screen at the beginning of each trial. An electronic device quickly removed the screen and at the same instant a clock (termed a chronoscope) would begin timing in steps of 1 ms. The response of the participant would then close a switch that stopped the clock. Cattell built a device that enabled the vibrations of the participant's spoken response to act as the signal that stopped the chronoscope so that he could measure the speed of verbal responding to a stimulus.

Cattell found that when participants were asked to identify (by naming) short words (say, between four and six letters in length), RT was no different than RT to name individual letters. He concluded that '*we do not therefore perceive separately the letters of which a word is composed but the word as a whole*'.

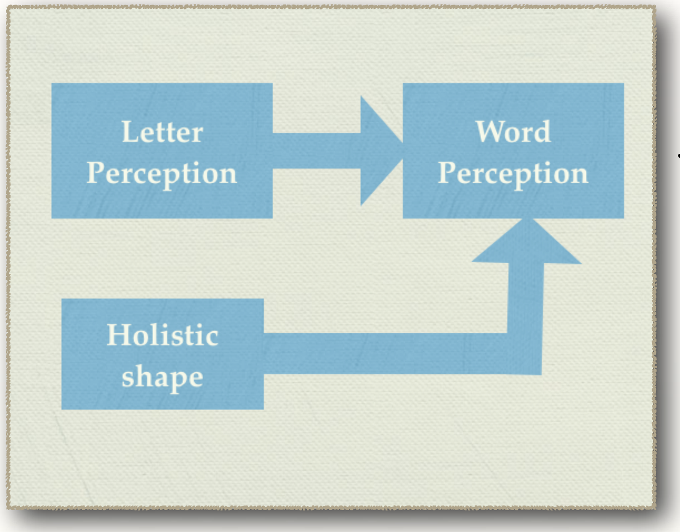
It turns out that a large number of experiments since Cattell's initial research on the identification of words and letters have demonstrated that words are actually perceived *better* than individual letters. Cattell's equipment was too crude to show the perceptual advantage for words. The effect (superior identification of a visual word relative to a letter) has been so widely replicated in hundreds of studies that it has been given a name and an acronym: the *word superiority effect* or *WSE*. Does this result mean, as Cattell inferred, that a word is seen by a skilled reader as a perceptual whole rather than as a string of individual letters?

There is an important mistake in Cattell's thinking about this evidence that we should unpack. In the diagram

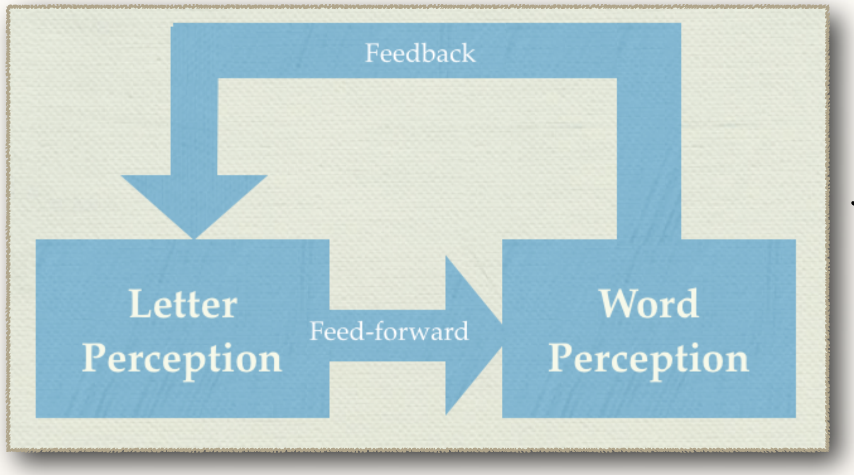


above, two stages are depicted, one for letters and the other for word identification. They operate *strictly in sequence*; the stage of letter perception runs to completion before word perception can begin. According to this little diagram, it is not possible for word identification to be *better* than letter identification because the stage of word processing depends on completing the earlier stage of letter perception.

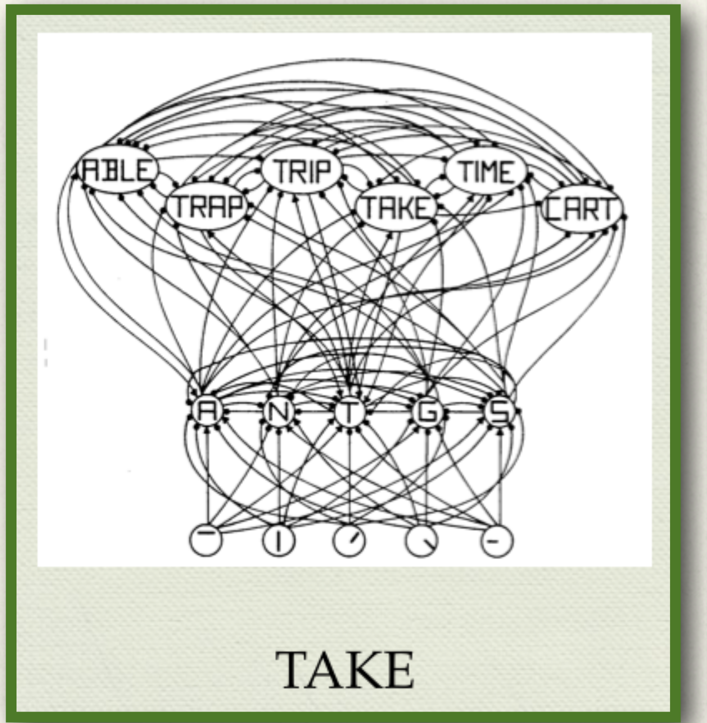
We call this arrangement of processing components *feed-forward* -- information flows in just one direction, from letter processing to words. Given this arrangement it is indeed the case -- as Cattell inferred -- that better perception of words than letters must imply that reading a word cannot depend on prior identification of its constituent letters. Instead, there must be another route from squiggles on the page to the identity of a word that bypasses letters, as depicted in the next diagram. We will assume this route involves a holistic perception of word shape. However, there is an interesting alternative that was not well understood during the early days of mental



chronometry. Consider the third diagram: There is a *feed-forward* connection from letter to word processing but in addition, the activation at the level of the word module *feeds back* onto letter perception. This type of functional architecture (we have used the term *functional architecture* before; if you are not sure of the meaning, check out the section on Lichtheim) is known as a *feed-forward/feedback* model of information processing.



We will consider in general terms how this arrangement can produce better perception of letters in words than a letter on its own. A more detailed analysis is presented in Case Study 14. Let us make a number of basic assumptions about the flow of information to and from letter and word processing mechanisms (*to and from* because the model has feedforward as well as feedback connections). First, we will assume that letters in a short word (say four letters in length) can all be processed at the same time rather than sequentially. The term for this type of processing is *spatially parallel* *processing*. Second, we further assume that information processing occurs in the two components of the diagram (Letter Perception and Word Perception) at the same time. Thus, it is *not* the case, that the word-level component of the system must wait to begin processing until letter perception is complete. Rather, as soon as *some* information begins to accumulate over the four spatial locations occupied by letters, words become activated, though at first there may be no single word that is activated strongly enough to produce a conscious percept.



An Interactive Activation Model of Reading

Case Study 14

We can say that *words are processed in parallel with letters*, but be careful to note that the term parallel processing in this sense means that several processing modules (in this case, the letter and word-level component) operate *at the same time* rather than in sequence to produce a response. The other sense of the term *parallel* refers to the fact that a *particular processing component* (in this example, the letter processing module) can operate on many *spatial locations* at the same time. Be sure to distinguish between these two different ways in which the term *parallel processing* is being used.

Consider how the model reacts to the visual word TAKE. As *letter perception* begins, not only will the letters T-A-K-E become active but so will other letter detectors that are similar in shape to these letters. For example, the letter F, will be partially activated by T, and so will E, because all three letters have some features in common (e.g. an upright 'post' - **I** - is a feature that is the same for all of them), R will be activated by K (both share the upright post and a diagonal 'foot') and so on. At the same time (because the processing levels in the model work in parallel), words become somewhat active, though none of them strongly enough to produce a definite response. The letters T-A-K-E will active the words LAKE, FAKE, TALE, TAME, TART, and many others.

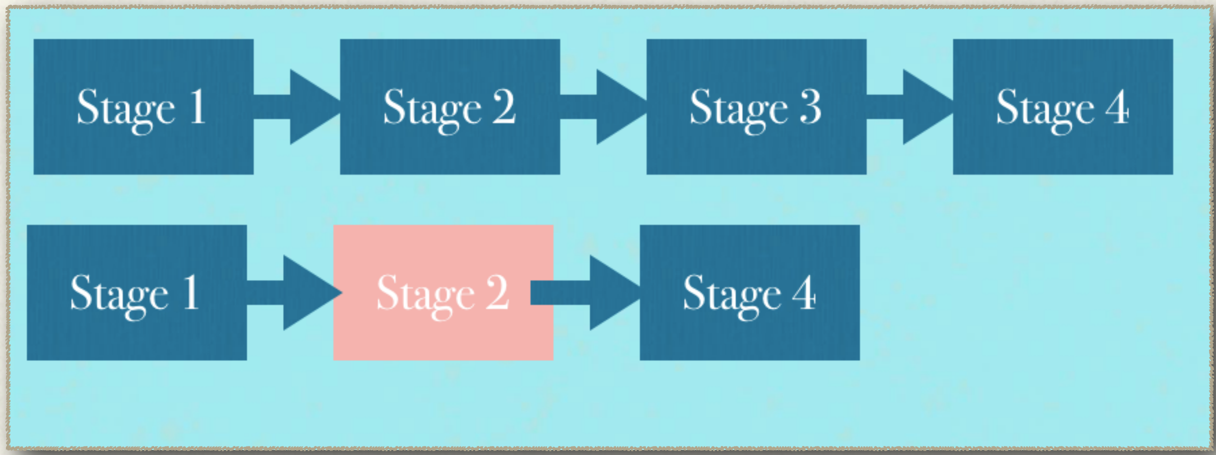
Now comes the interesting part. These partially excited words *feed their activation back* onto letter detectors. That means the letter sequence A-K-E will receive very strong feedback support from the words TAKE, FAKE, MAKE, RAKE, and so on, all of which have been activated to a lesser or greater extent by the array T-A-K-E. The letter T will receive feedback from the activated words TAKE, TALK, TAME, TALE, TALL etc. This *feedback from word units back to letter units* enhances the activation within the letter processing module. These strongly activated letter units will in turn combine to enhance the strength of the activation of the word unit TAKE, which then feeds more activation back onto letters. The feedforward/feedback cycle continues until the system rapidly settles on to the correct target. An isolated letter as a stimulus or a random string of letters has no such feedback from word-level representations to enhance the strength of activation over time, and the net result is the well known WSE.

Additive Factors

The previous section describes two processing components which interact, in the sense that word-level activation influences the *prior* stage of letter recognition. This type of feedforward/feedback processing loop is an important part of the brain's speed and efficiency, despite the rather sluggish neural transmission time first documented by Helmholtz. Because multiple stages of processing work interactively and at the same time, the brain rapidly settles on a response to a perceptual event.

Not all stages of processing interact in this way, of course; there are definite bottlenecks where one stage cannot begin to operate before a previous stage has run to completion. Recall that the *logic of subtraction methodology* requires us to assume that: (i) processes are sequential so that the output of one stage acts as input to the next and (ii) only one process is active at a time. Assuming these conditions are met, how should we proceed to obtain further insight into the organization of different processing stages that occur between stimulus input and response output?

It has been established that Donders' subtractive method has some fundamental problems. The main one, as we have seen, concerns the argument of pure insertion: that adding (or removing) a processing stage from a sequence will leave other processes unaltered. The figure above depicts

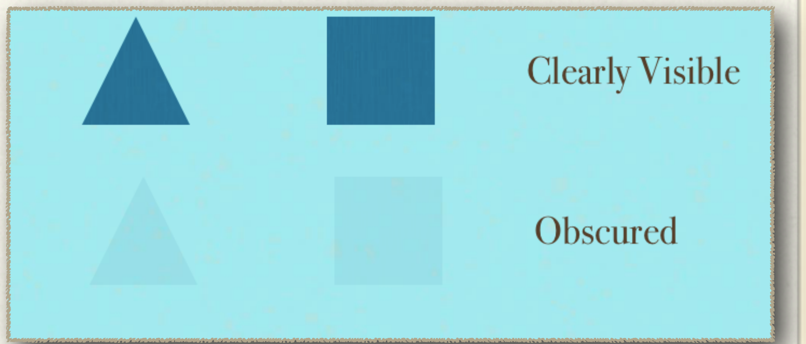


Removing a processing stage (in this example, Stage 3) may well alter one or more remaining stages (in this example, Stage 2)

that this is often not the case; removing Stage 3 in this example, alters the nature of processing at the level of Stage 2. It follows that subtracting the average RT's of two different tasks will generally not tell us much about underlying mental processes.

Donders had no statistical methods available to go beyond subtraction methodology. The development of additional analytic tools provide the modern foundations of mental chronometry. A discussion of these techniques is presented in Case Study 15. They are based on the general idea that it is possible to systematically vary *an experimental factor* so as to affect a particular processing stage. For example, consider again Donders' choice reaction time task. Recall that participants must produce one response to a stimulus event (say, a triangle) and another response to a different event (e.g. a square). Hypothetical stages involved are: Stimulus Identification, Response Selection and Response Execution.

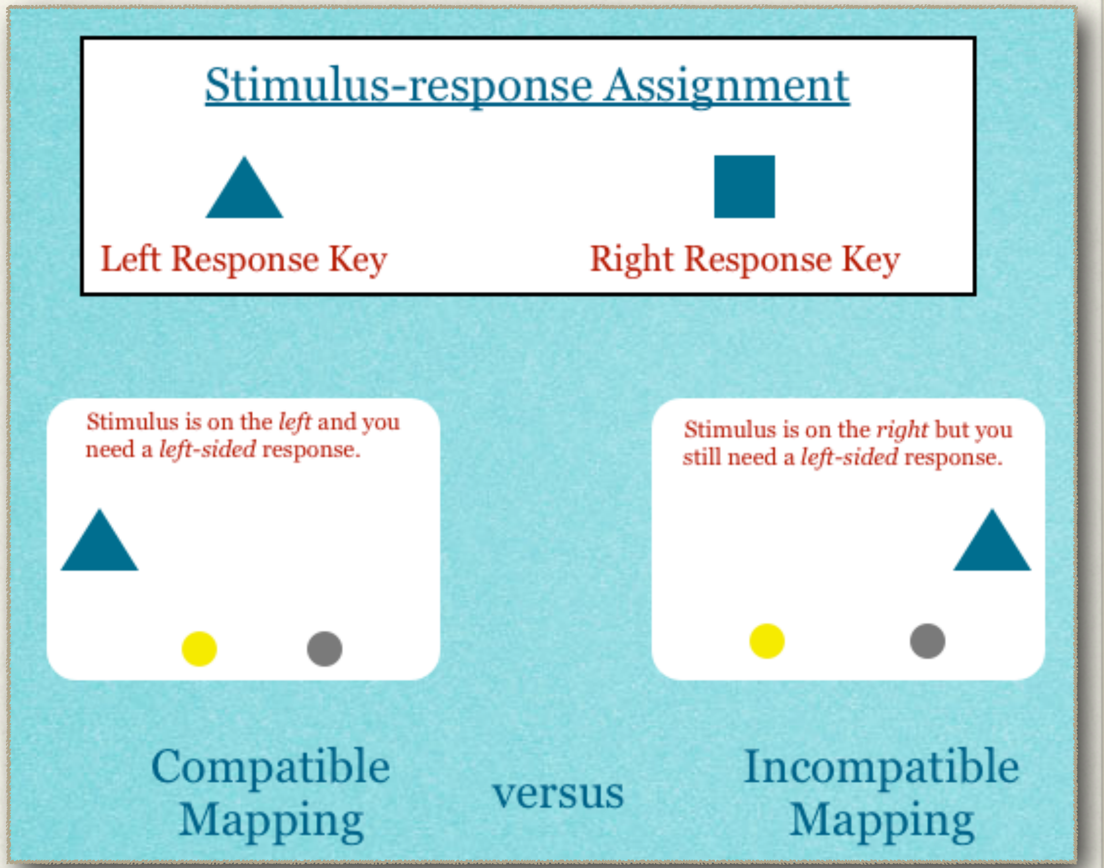
One *factor* that could be varied concerns the *quality of the image* affecting the stage marked *Identification*. The triangle and square could be presented clearly on some trials or rendered harder to see (obscured) on other trials. We can call this factor *Stimulus Clarity* and it has *two levels* (Clear versus Obscured).



A *stimulus* factor affecting the stage of Perceptual Identification

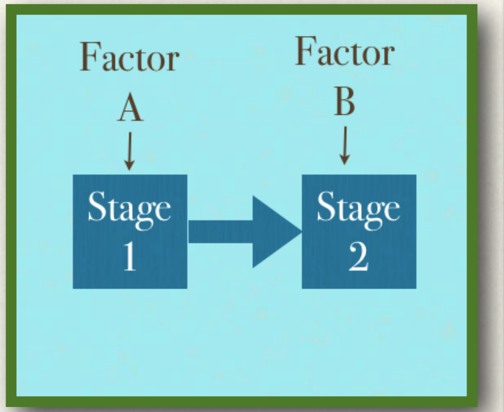
The participant's *response* is to press one key to signal the identity of the triangle and another key for the square. Obviously it will harder to identify an obscured object than the same object that is clearly visible.

An experimental factor that will affect *Response Selection* is to make the *choice of response* easy or hard for the participant to decide on. Suppose we assigned the triangle to a Left Response key and the square to a Right Response key. On some trials we presented the target object on the left of the display, other trials on the right. A *spatially compatible mapping* between the stimulus and response would occur when the target is on the left and a left-sided response is required, or when it is on the right and a right-sided response is required. A *spatially incompatible mapping* occurs when the target is on the right but a left-sided response is the correct choice, or the target is on the left and a right-sided choice of responding is needed. A compatible stimulus-response (SR) mapping is easier than an incompatible SR mapping.



A *response* factor affecting the stage of Response Selection

We have two *factors* then: *Stimulus Clarity* and *Response Compatibility*, each with two *levels*, and each of which is designed to affect a particular processing stage. The *logic of additive factors*, discussed in Case Study 15, can be used to test whether two stages function independently of each other or whether they do not in fact operate as distinct components of a functional architecture.



Additive Factors Logic

Case Study 15

Notice the wording of the previous sentence. Two processing stages linked together in a feedforward/feedback cycle will not *operate* independently of each other. Yet they may certainly exist as distinct components of a functional architecture, at least in the sense that each component relies on different *kinds of information*. The identification of individual letters requires the visual system to extract *distinctive features* that are common to different shapes. For example, A, A, A, A, A, A are easily recognized as the same item despite their differences in appearance. The identification of a word includes a stored representation of the *order* of a *sequence* of letters: EAT, TEA, ATE, all have the *same letters* but are quite *different* at the word level. We can certainly infer, then, that the processing of a word requires the brain to access a *qualitatively different kind of information* than the visual features needed to perceptually identify letter shapes. In that sense, letter-level processes must be modularly distinct from word-level processes even though the two levels operate interactively. While mental chronometry may not easily disentangle processes that work interactively, the methodology is just one amongst many techniques that can be used to understand the architecture of complex information processing systems.

Word Superiority Effect Demo