Perceptual fulfilment and temporal sequence learning

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Contents:

1. Summary   What happens when an expectation of a certain perceptible event is fulfilled? Traditional empiricist theories about intentionality, as well as several recent theories about mental imagery, emphasise the concrete similarity between expectations and perceptions. For example, one can almost "hear in one's head" a melody which one is anticipating. This has been the starting point for many theories which postulate some kind of similarity matching between the expectation and its fulfilment. According to such theories, an analogue mental representation of the expected fact is "held up" against the incoming percept, and their similarity or non-similarity determines whether the expectation is or is not fulfilled.

If such theories are taken as descriptions of phenomenologically accessible facts, they are difficult to defend. First, analogical expectations - when they do occur - usually do not persist into the fulfilment phase. And how could they be matched for similarity, if they are not available at the same time? Second, many cases of expectation do not involve any imagery at all but only reveal themselves as a feeling of surprise if they are not fulfilled.

The philosophical literature abounds with arguments against the thesis that concrete similarity to a certain percept is essential for an expectation to have that percept as its object. But of course these are not arguments against cognitive and/or neural-network theories which entail that simultaneous matchings are performed below the introspectively accessible level; such an assumption is often used in explanations of perceptual learning.

I here suggest a simple alternative theory of the nature of matching in such learning. Suppose that thought and perception alternate using the same representational medium, and that the contents of this medium are being continuously fed into the cognitive system which produces thought. Such a common feedback/input mechanism will, in itself, give rise to learning because at each alternation from expectation to perception, the system will perform an implicit matching. If the percept is sufficiently dissimilar to what would have occurred in the common medium without perception, the cognitive system will tend to switch to another region of its state-space, in which other kinds of expectations are produced.

This learning process can take care of certain "hard" learning problems, especially, the associative learning of temporal perceptual patterns. I have suggested the name "natural resonance" for it (Malmgren 1991, 1996).

2. Phenomenology of expectations   Suppose that you are familiar with a certain recording of Beethoven's Fifth Symphony, and that you are just going to play it on the gramophone. Your expectations before it starts may well manifest themselves in the form of a temporally extended, clear and distinct imaginative presentation of the first five bars, "hearing them with your inner ear":

This hearing with your inner ear is a process which is very similar to the actual

hearing of the first five bars; for example, it takes approximately the same time and is accompanied by similar emotional reactions. When you listen to the actual music, the similarity may even strike you. But no copy of the original experience is displayed in parallel with the actual music. That would make a split mind, or at least a duo of every sonata.

Also think of the case of a violinist playing the solo part of a concerto. Before the performance, he certainly rehearses it both physically and mentally. But while he is playing, his running internal anticipation of the next notes cannot possibly take the form of a continuously updated analogical rehearsal of these notes. Again, that would require a double musical consciousness. A fortiori, the fact that one of his anticipations is verified cannot consist in a match between an image and a percept.

But then, what do we have analogical expectation for? My explanation is that the basic function of intentionality is to substitute for perception when no external information is coming in. For this it had better use the same system as perception, which tends to make expectations like percepts. A typical example is offered by walking while talking philosophy. You only have to visually attend to the road once in a while in order to update the internal picture of it. In between, the internal image works as well as a percept. The image is even as dynamic as the percept. If you just saw a stone in front of you, you can if you want still see the stone coming closer before your internal eye. But even if you don't think of it, you usually succeed in avoiding the stone.

The last-mentioned fact also means that during the walk, an analogical expectation and the fulfilling percept often differ. You see a stone at some distance, you form a corresponding image of it, and you set your steps so as to avoid it. Then you concentrate on the philosophical talk. When the stone is close you take a verifying look at it. It is as big as you expected. But your image was small - how can they match, if they are so different?

3. Matching in analysis-by-synthesis models   MacKay (1956) outlined a model for automaton learning which involves the comparison between the environment and an internally produced representation. An error signal is sent as input if a mismatch occurs. If the environment is reasonably stable this error signal (or repeated such signals) may lead to an adaptation in the sense that the internally produced representation eventually matches the environment. In cognitive science, this general scheme has become known as the "top-down" or "analysis-by-synthesis" model. As MacKay himself points out, the model can be

developed in several directions depending (among other things) on how one conceptualises the error signal.

Among recent ideas which conform to MacKay's concept are Grossberg's "adaptive resonance" theories (ART; Grossberg 1987). The input ("bottom-up") signal first activates a number of high-level neurones, and the neurone with the largest activity is selected by competition. The selection process is a matching in an abstract sense, since the neurone with weights which corresponds best to the input activity vector becomes the winner. In a second step, the "top-down signal" from the winning neurone is compared to the input. This step involves a matching in a more concrete sense, since the corresponding activities in two sets of neurones are being compared. (Two isomorphic hardware structures are needed!) If there is a large enough mismatch an error signal is sent, signifying that the input does not belong to any known category.

Kosslyn (Kosslyn 1994) postulates a process which is similar to ART in many respects, but also essentially different. In perception, the perceptual data in the visual buffer are first "bottom-up matched" to prototypes and exemplars stored in the "pattern activation systems". This is an abstract matching since the stored patterns are coded as network weights. If the first match is poor, the pattern activation systems generate an image in the visual buffer. According to Kosslyn, this image is not itself compared to the input, but simply "fills in" or "completes" the externally generated data (p. 121). It is true that his model also allows for a set of mechanisms for top-down hypothesis testing in certain perceptual situations (pp. 225 ff), but these mechanisms do not include a concrete image/input matching.

As shown above, simultaneous concrete matching requires duplicate systems. Hence I guess that Kosslyn's reluctance to believe in such a process is connected with his main thesis - with which I certainly agree! - that imaging uses the same brain system as perception. But if one rejects simultaneous concrete matching, how should one conceptualise the relation between analogical expectations and their fulfilling events?

4. Natural resonance   In the present theory, too, the central cognitive system and the external world are modelled as feeding their data into a common medium. I will refer to the common medium as the "resonator" or "resonant element". In the simplest versions of the theory, the state of the resonator is supposed to be completely input-dependent, i.e., it has no memory of its own. The central (memory) system is a deterministic machine, taking its input from

the resonant element. At each moment, the state of the resonator is determined either by the output from memory or by the input from the external world (the "external input"), but never by both. This is intended to be the counterpart (in the simple theory) to the alternation between thought and perception described earlier. Most importantly, the state of the resonant element is being continuously fed back to the memory system. Think of this as corresponding to the phenomenological fact that one does experience both the perceived world and the imagined one. (The resonant states can also be states of a motor apparatus, allowing for learning of behavioural routines.)

To explain the working of a naturally resonant system in an simple way, I will now describe the case of a finite-state machine learning to follow an external rhythm. The system is illustrated below.

A finite-state resonant system learning an external rhythm
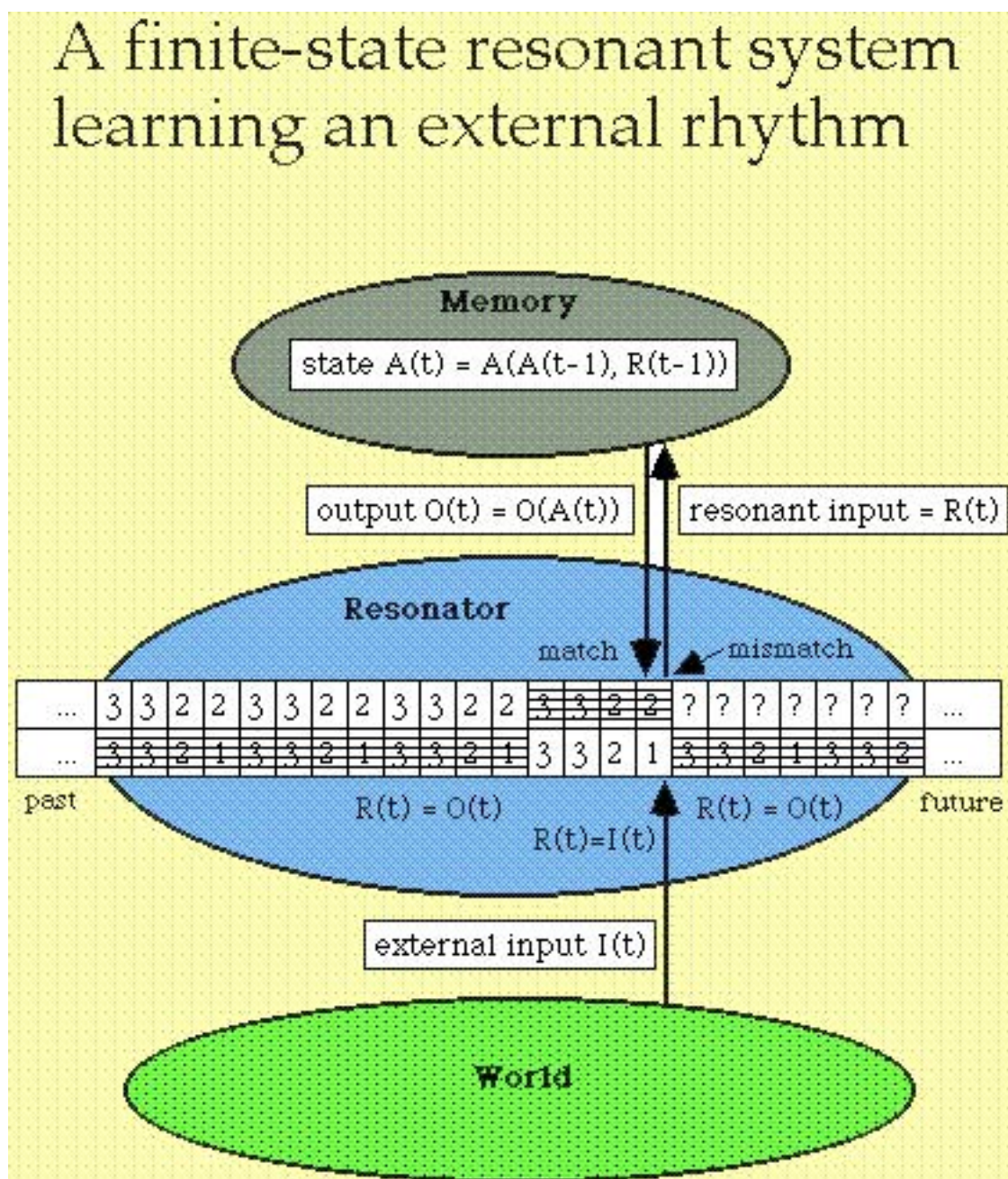
Let us denote the resonant states with "1", "2" etc. While "thinking", the system's behaviour is completely state-dependent. So, if it thinks for a sufficiently long period it eventually becomes confined to one of a number of possible limit cycles, where one state rigidly follows upon another. The outputs, seen in separation, need not by themselves constitute such a deterministic (first order Markov) machine; a "2" may be sometimes followed by a "2", and sometimes by a "3". But the output sequences will repeat themselves in a determinate manner, forming a more or less complex rhythm. In the example, the internal rhythm is "3322..."

A short period of perception begins and an external rhythm is heard, giving rise to a sequence of states in the resonator. Now, the sequence produced by external input during this period may be the same as - and in phase with - that which the memory would have produced, had it not been disturbed in its thinking. If so, the memory will not "notice any difference". If on the other hand there is a difference between the actual resonant state and the state which would have been produced by thought, the memory system may react to the different feedback by switching to another one of its possible limit cycles. So, a selectional process has been set in motion, which ends if an internal cycle is found which corresponds to the external rhythm; the basis of this process is that the system performs an implicit comparison between the actual input and a possible one.

5. Natural resonance and "intelligent" learning   A simple naturally resonant system consists of an input-dependent deterministic machine A (memory), whose input R is at each time fully determined either by the transduced external input I (under the external constraint) or by the feedback from its own output O (under the "free-running" condition). Above, I have illustrated the finite-state resonant machine described above while learning the rhythm "3321".

The process described here is not intelligent, since the search for a solution has no specific direction and there is no guarantee that a solution will be found or even approached. This is not a problem which belongs specifically to the present model; for example, any traditional top-down model using error signals from a simultaneous comparison must also face it. Positively, solutions used in other theories might be transferred to resonance models. It is however not my aim to discuss in general terms how resonant systems could be built which show gradual learning, but only to point to a new and potentially fruitful way of conceptualising the error signal.

The argument used above to show that a resonant system can learn an external rhythm is actually valid for any outer constraint (invariant): if the system has a built-in capability to stably produce internal outputs which conform to the external constraint, it will tend to move to the region in state space where it does so, and to stay there. I will conclude my poster by illustrating this for invariants of the form "A is followed by B".

6. Conditioning   It is generally believed today that feed-back networks are required for sequential tasks. However, there are as yet no biologically realistic models of error-correction in such networks. One advantage of naturally resonant systems is that they always use sequential information to correct their errors. Hence, they can be conditioned to specific input sequences. In a conditioning simulation (Malmgren 1991), randomly composed finite deterministic systems were used. Their transition tables were built in a uniformly random way except that for one input ("background") they were biased towards remaining in the same state. A large number of these machines were exposed to the background, interrupted by periods of "DBA" and "DB". At five progressive points of time it was noted how many systems stably outputted an "A" after having received "DB". As a control, it was checked at time 6 whether the systems stably produced "A" after having received "BB". The machines did tend to specifically learn DB => A; with 5000 systems the results were:

Time	1	2	3	4	5	6
DB => A	143	603	665	699	712	
BB => A						176

Let me conclude with a speculation. The input to the brain follows paths which pass several relay stations and which converge and diverge in a very complex way. This allows for the coding of a huge number of different external invariants. Similarly, a great number of invariants can in principle be simulated in lower centres using the many feedback connections. With such huge potential capabilities available to mirror outer constraints, natural resonance may be a powerful learning tool and the basis of many of our adaptive abilities.

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