The Economy Principle, Perceptual Mechanisms, and Automated Cognitive Processes

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Abstract

The question why the processes in perception and cognition have evolved the way they are has led to the suggestion of two major categories of underlying principles. One is the 'principle of least effort' stemming from physics and applied to a host of phenomena in psychology (see the work of KÖHLER or of ZIPF to name only two extremes starting from the same principle). Alternatively, stressing the survival value provided by perceptual and cognitive processes leads to an evolutionary approach (e.g. KOFFKA). SHEPARD's notion of 'psychophysical complementarity' elucidates the necessary interactions of both kinds of constraints in perception and cognition.

The generalization of this approach to the development of perceptual and cognitive skills on different levels of complexity leads to three models of hierarchical integration: (i) a building-block model of goal-directed upward integration, (ii) a model with upward integration in the initial stage of development but downward constraint propagation lateron, (iii) the same as (ii) plus a horizontal constraint propagation under the restriction of resources necessary for execution.

Data from experiments on the perception of perspective and of symmetry as well as on the acquisition of motor skills favor model (ii) and cancel out model (i). Preliminary results on automated behavior under the restriction of resources indicate, however, that in general model (iii) might be the appropriate.

The development of the scientific investigation of perception at the turn of the century in Germany was characterized by the search for unifying principles underlying perception. The discovery of transposability as the crucial condition for Gestalten made it necessary to look for more abstract principles in perception than mere mappings from physical units into perceptual units. KOFFKA (1935, p. 76) pointed out that the ultimate goal for any theory of perception is to answer the question "Why do things look as they do?"

The principle of least effort which underlies and unifies classical mechanics strongly influenced the development of KÖHLER's theory of perception (for the application of this principle to behavioral phenomena, see ZIPF 19). Especially in 'Die physischen Gestalten in Ruhe und im stationären Zustand' (KÖHLER 1920), he suggested that perceptual organization is characterized by the minimal amount of work necessary for maintaining a pattern in a steady state. An example from physics for such a kind of organisation is the formation of spherical soap bubbles.

KOFFKA (1935, p. 171-174) in discussing "Prägnanz" partially followed KÖHLER's physicastic approach in the investigation of the relation between static organization and certain maximum-minimum principles of simplicity. However, in contrast to KÖHLER he suggested an evolution-theoretic framework for the processes underlying perceptual and cognitive organization by asking for the survival value of these processes. Both approaches stress what has been termed the aspect of economy in psychological processes. However, neither of the suggested principles allows for a direct test. In order to bridge this gap, different approaches have been suggested to make possible indirect tests of the principles underlying organization in perception and other cognitive processes.

The seemingly most straightforward interpretation of the principle underlying the 'Prägnanz' ('singularity', GOLDMEIER 1982) of a pattern is to assume that it is redundancy as defined by information theory (SHANNON 1948). ATTNEAVE (1954) and HOCHBERG & McALISTER (1953) have investigated this aspect of figural "goodness" and found a strong relation between the amount of information (number of free parameters) characteristic for a given form and its judged figural goodness. GARNER (1974) has taken a different approach to the measurement of information in visual forms, namely by determining the rotations and reflections under which a given pattern remains invariant. Here information is defined by means of degrees of freedom.

Both definitions of information are independent of the spatial orientation of the figures. However, MACH (1871/1903) was the first to point out the difference in saliency between vertical and horizontal symmetry. CORBALLIS & RORDAN (1975) and ZIMMER (1984 a) have reported functional relations between the orientation of a form and the detectability of its symmetry. ZIMMER (1984 a) furthermore has shown that the effect of the spatial orientation can at least partially be counteracted by induced frames of reference. PALMER (1983) has integrated GARNER's transformational model and the results on orientation effects into a model in which figural goodness is defined by the transformational group and an orientation dependent two-dimensional weighting function.

One consequence of the transformational view of figural "goodness" in general and of symmetry in particular is that all kinds of symmetry (e.g. bi-lateral, rotational, and repetetive) can be produced by sequences of reflections and rotations (VIOLA 1904). If this were true for perceived symmetry, too, then the economy in perceiving symmetric or 'good' forms would lie in the amount of effort saved by scanning only the non-redundant parts of a form. The results of LOCHER & NODINE (1973) apparently support this conclusion. However, experiments comparing the identification times for visual forms which are either perfectly symmetric but of different kinds of symmetry or non-symmetric, reveal that the superiority of the symmetric forms vanishes if the subjects do not know which kind of symmetry to expect (ZIMMER, in preparation). This result indicates that in general the abstract redundancy of a pattern cannot account for the behavioral effects of figural 'goodness'. Obviously, there are effects of each kind of symmetry but these effects cannot be attributed to symmetry in general but only to the specifics of the different kinds of symmetry.

Investigations in the role of symmetry in biology (e.g. LUDWIG 1949) make it plausible to assume that the different kinds of symmetry do not only serve different functions in the morphological evolution but furthermore that the visual perception of these different kinds of symmetry serves different functions for the survival, too. Given this, it follows that the identification of the economy principle with a general measure of abstract information is misleading or, at least, only valid for experimental situations in which the complexity of the stimuli as well as of the tasks can be held very low. One common procedure for controlling the complexity of visual stimuli in experiments is to use pictures. However, two-dimensional displays are evidently not the ecological objects our visual perception was evolutionarily adapted to. GIBSON has criticized this paradoxical situation vehemently (see e.g. GIBSON, 1979) and has claimed that 'seeing' 3-dimensional objects in 2-dimensional displays is the natural way of perceiving pictures. According to him this way of perceiving can only be overcome if one fools the subject by playing on what METZGER calls 'the love of order in our senses' (1975, p. 405).

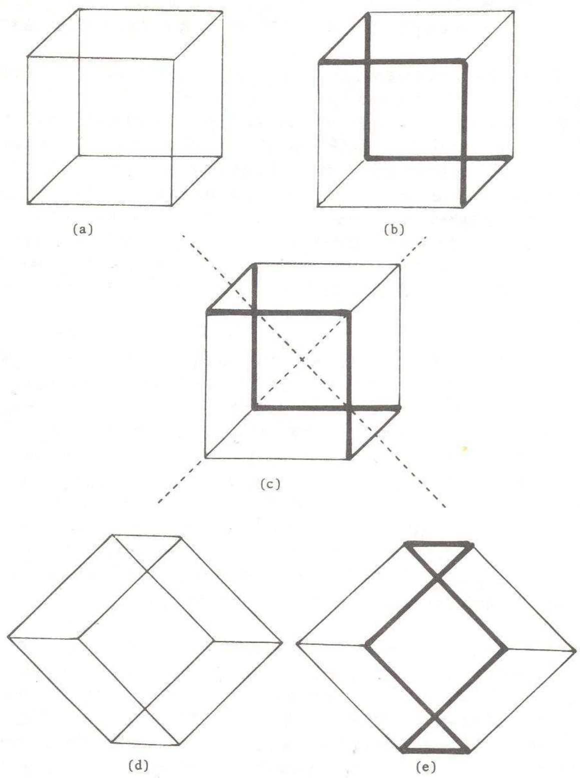

Figure 1 Line drawings of a cube which elicit differently strong spatial impressions

Figure 1 shows how a line drawing of a cube (a) is still 'seen' 3-dimensionally if the figurally 'good' parts are emphasized (b). Adding the axes of symmetry of the line drawing (c), which are different from the axes of symmetry for the cube, leaves the 3-dimensional impression still unharmed. Only if the figure is rotated in such a way that the 2-dimensional axes are in the orientation which makes symmetry most salient (d) and if furthermore the figurally 'good' parts are additionally emphasized (e), the 'sense of order' prevails over the 'natural way of viewing a picture'.

This example indicates how the figural 'goodness' of parts interacts with the global perception of the complete form. NAVON (1977) has shown that usually the perception of global features precedes over the perception of local features. However, this 'forest-before-tree' effect seems to depend on the relative figural 'goodness' or the relative meaningfulness of the global and the local features. The question is how the architecture of a perceptual system ought to be which accounts (i) for the described phenomena and (ii) for the veridicality of perception which makes survival possible (KOFFKA, 1935, p. 76 "Why do things look as they do?").

From what has been said it becomes apparent that this system has to encompass distal and proximal stimuli as well as their internal representation and furthermore the relations between them and the possible transformations they can undergo. For this psycho-physical problem SHEPARD (1981) has suggested the principle of complementarity: "The designation of the relation between corresponding internal and external structures as one of 'complementarity' attempts to capture these two aspects of that relation - namely: (a) that the two structures, existing in necessarily disjoint domains, cannot be directly compared; and (b) that they must nevertheless be capable of a very precise and efficient mesh at the lower-dimensional common boundary" (SHEPARD 1981, p. 331). He answers KOFFKA's question by debunking the Rationalist as well as the Empiricist reduction of the problem. "(1) The world appears the way it does because we are the way we are, and (2) we are the way we are because we have evolved in a world that is the way it is" (SHEPARD 1981, p. 332). SHEPARD proposes a model (Figure 2) for the relation between external objects (A, B, C) proximal stimuli (A', B', C'), and internal representations (A", B", C").

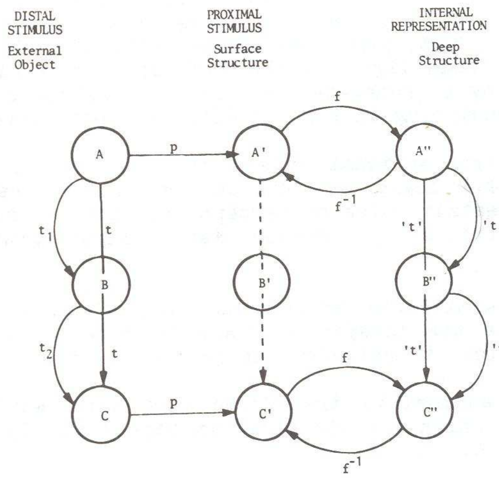

__Figure 2__ Schema of the projective (p), formational (f and f^{-1}), and transformational (t and 't') mappings between external objects (A, B, C), proximal stimuli (A', B', C') and internal representations (A", B", C"). The concatenation of transformations of external objects ($t_1 + t_2 = t$) is the same as the concatenation of transformations on internal transformations ('t_1' + 't_2' = 't'). (SHEPARD 1981).

According to this model the complementarity of external and internal transformations (t and 't') makes possible that the internal representations preserve the essential properties of the external 3-dimensional objects despite the 2-dimensionality of the interfacing proximal stimuli. SHEPARD's and his students' research on mental rotation and apparent movement (for an overview see SHEPARD 1981) supports this model and explores the survival aspect of perceptual and cognitive processes as well as the minimization principles governing these processes (e.g.

minimal pathways in apparent motion). The model does not make explicit what the internal representations are made of (LEEUWENBERG's coding theory (1971) might be a possible candidate for this) and it does not explore the role of knowledge and experience in the development and modification of the internal representations.

For the interaction of external objects, knowledge, and action NEISSER (1976) has suggested the perceptual cycle according to which available information (of external objects) modifies internal schemata. The schemata in turn direct explorative action which sample available information from the environment. The central concept of this approach is the schema as a structure in memory which controls the active processes in perception (NORMAN & BOBROW 1976). The definition of a schema as given by CASSIRER (1944) in a group-theoretic approach to perception seems to capture well what is implicitly assumed in NEISSER's (1976) usage of the term. Paraphrasing CASSIRER (1944), a schema consists of:

(i) a set of primitives which are not further analyzable in the given context of perception (e.g. in the context of line drawings of geometrical solids vertices, angles and lines can be regarded as primitives in spite of the fact that certain lines might be virtual lines, for instance, consisting of a linear change in texture (see GREGORY 1973, pages 89 and 90; GOMBRICH 1973, pages 236 and 237). This sheds light on the fact that on a different level in the hierarchy of schemata the lines themselves can be regarded as schemata consisting in turn of different primitives).

(ii) a set of organizational rules which can be paralleled to HELMHOLTZ' (1896) logic of 'unconscious inferences' in perception (e.g. the Gestalt rules of perception: closure, similarity, symmetry, proportionality, common fate, figure-ground distinction, etc.).

(iii) a set of admissible transformations, that is, transformations which define the invariance class of objects in question (KATZ 1930) rotation, translation, projection, etc.

How the sets of admissible transformations differentiate between two different schemata which are identical in regard to (i) and (ii) becomes apparent in Figure 3.

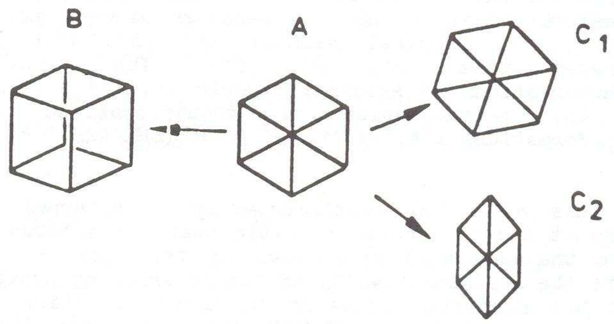

Figure 3 Possible transformations for drawing A:
B if interpreted as a cube drawing
C is interpreted as a hexagon with spokes

If the transformation of A into B is admissible, then the schema is a 'line drawing of a cube', if on the other hand only rotational transformations in the plane or in three dimensions are admissible as in C_1 or C_2 then the schema is a 'hexagon with spokes'.

RESTLE's (1983) analysis of LEEUWENBERG's coding theory appears to be very similar to CASSIRER's (1944) schema theory. The crucial difference, however, lies in the fact that in coding theory the principle of minimal information serves as an explicit mechanism of organization whereas in schema theory there is no a-priori rule which confines the set of admissible transformation. One could assume that schemata are self-organizing in the sense of PRIGOGINE & STENGERS (1984, p. 300).

If one takes schemata as the building blocks of cognition as RUMELHART (1980) suggests, it is necessary to ask for the rules which govern the 'architecture' of cognition and for the the role of the principle of economy in it.

The most simple rule of schema integration is the hierarchic agglomeration of lower-level schemata as depicted in Figure 4.

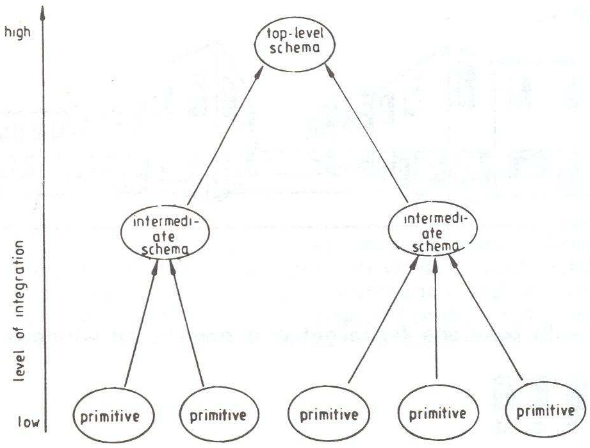

Figure 4 Schema of the postulated integration process underlying complex perceptual processes, skill acquisition, and heuristic processes. The arrows with straight lines indicate the upward integration.

FODOR (1983) in his concept of modularity in cognition or PYLYSHYN (1984) in his theory of computational perception seem to adhere to such a model of knowledge integration. The advantage of such an internal organization is that the integration keeps the components unchanged and therefore makes decompositions and novel integrations possible. Furthermore there are only few and simple organizing processes which are repeated over and over. That makes their 'cost' in mental computation extremely cheap (see NAVON & GOPHER 1979). In order to test this model, it is necessary to choose a domain in which perceptual and cognitive tasks are intricately connected and can be assumed to change under the influence of experience. Such a domain is the coordination of perception and motor actions in skilled behavior. BURTON, BROWN & FISCHER (1984) have discussed the implications of such a model for learning and coaching how to ski.

ZIMMER (1983, 1984) and KÖRNDLE (1984) have investigated the dynamics of cognitive processes in the acquisition of motor skills. Their results indicate that the purely agglomerative model of knowledge integration only holds for the initial phase of learning. Lateron the lower-level schemata become modified and are no longer separable from the schema hierarchy. ZIMMER (in press) has shown that in complex tasks as, for instance, visual search in naturalist settings, perception and internal schema processing form and intricate mesh in the sense of SHEPARD (1981, p. 331). In this situation lower-level schemata (e.g. windows) are no longer represented in their canonical form and orientation but in the distortions imposed on them by higher-level schemata (e.g. perspective).

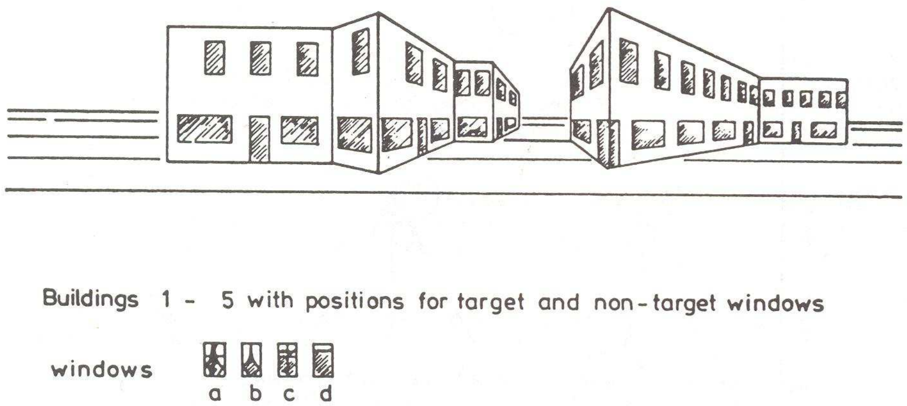

Figure 5 Display for a visual search task (ZIMMER, in press). The target and non-target windows were shown in the positions on the second floor. Distractors were non-target windows and not perspectively distorted windows of the same form as the target windows. Subjects had to identify the building with the target window as soon as possible.

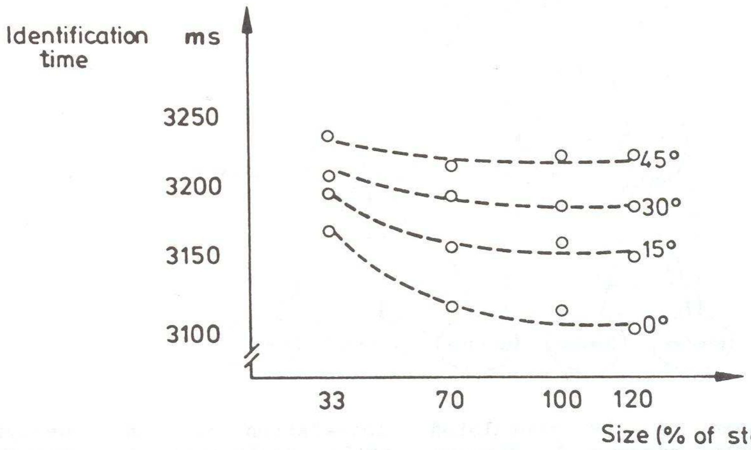

Figure 6 Results from the visual search task. None of the subjects reacted to the non perspectively distorted distractors. The influences of the size (abscissa) and of the distortion angle of the targets are significant, but extremely small in comparison with the overall search time.

Figure 7 shows how this kind of schema integration can be modelled.

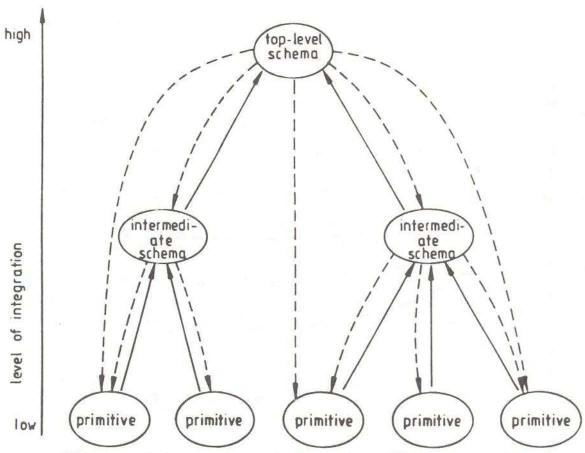

Figure 7 Schema of the postulated integration process underlying complex perceptual processes, skill acquisition, and heuristic processes. The arrows with straight lines indicate the upward integration. The arrows with the dotted lines depict possible downward constraints on the admissible transformations of the subordinate units.

In this graph schemata are integrated upwards into a schema hierarchy which leads to a reduction of the complexity of the system and finally to an automatic execution of the task. However, parallel to this kind of upward integration the higher-order schemata impose constraints upon the set of admissible transformations in the lower-order schemata. Such a hierarchy with upward integration and downward constraints is not decomposable in the sense of SIMON (1965). If for a different task only some of the lower-level schemata are necessary, they cannot be easily separated from the schema hierarchy they are part of.

The consequences of decomposable vs. non-decomposable representations of motor skills have been investigated by KÖRNDLE (1984) and by ZIMMER (1984). The general hypothesis underlying their experiments is that the described model of schema integration underlies the acquisition of skills. The practical consequence of this model is that complete transfer from one task to another is only possible if both tasks are admissible transformations of the same schema. Partial transfer (i.e. some but not all subskills necessary for one task are necessary for the other) is only possible as long as the subskills are not integrated into the superordinate schema, that is, automatized.

One consequence of this model is that in tasks or situations with restricted resources the allocation is controlled on each level, that is, horizontally but depending on the downward constraints (see Figure 8).

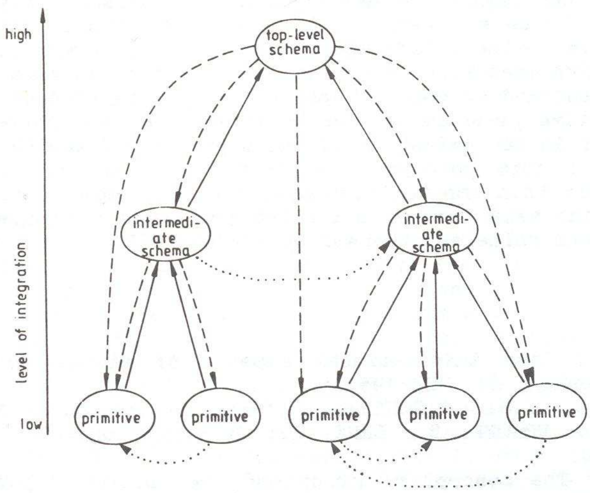

Figure 8 Schema of the postulated integration process underlying complex perceptual processes, skill acquisition, and heuristic processes. The arrows with straight lines indicate the upward integration. The arrows with the dotted lines depict possible downward constraints on the admissible transformations of the subordinate units. The dotted lines indicate the sequence of execution of processes on the same level.

The described model of schema integration makes plausible why automated processes do not interfere with other processes (KEELE 1973; SCHIFFRIN & SCHNEIDER 1984). The reason is that the downward constraints and the horizontal control structure rigidly determine the allocation of resources. Because of this property the execution of perceptual of motor actions becomes 'cheap', that is, needing only a small part of the allocatable resources. In comparison, the same actions performed according to the purely agglomerative model would consume more resources because in it the allocation of resources needs attention.

The described model of schema integration highlights the benefits as well as the drawbacks of resource-economic processes. The overcoming of capacity constraints, the speed in execution, and the accuracy due to the lack of interference have to be paid for by a general lack of flexibility, cognitive fallacies (TVERSKY & KAHNEMAN 1983), functional fixation (DUNCKER 1945), and mental set (LUCHINS 1946). These negative consequence of the economy principle are not confined to 'higher' cognitive processes. They can be found in comparatively basic perceptual processes (e.g. optical illusions) and they are not confined to humans (see e.g. the effects of camouflage in animals where the charistic form of an animal is broken by patches or stripes, see HINTON 1973).

A comparison of the benefits and risks which go with the economy principle in perception and cognition makes it compelling to ask for the selective mechanism underlying the development of processes obeying this principle. It seems to be a general biological fact that in animals the resources allocatable to the intake and processing of information as well as for the consecutive execution of actions are limited. In such a situation the more frequent and/or more general events can be assumed to exert the strongest selective pressure on the development of the corresponding processes leading to an economization of these processes. KÖHLER's (1920) soap-bubble model of form perception appears to be an important, but specific mechanism in this imputed economization. The more general principle seems to be the selection of automated processes according to the corresponding survival value as stressed by KOFFKA (1935).

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