GESTALT FACTORS IN HUMAN MOVEMENT COORDINATION[1]

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Introduction

Gestalt factors such as the principles of closure, nearest neighborhood (proximity), good continuation, and common fate, are widely regarded as being tailored and well-suited for guiding the perception of spatial and temporal patterns. In this view, Gestalt factors are rules that the brain uses for reducing the overwhelming complexity of the perceptual world. Or, speaking in terms of information theory, these rules allow for highly effective information compression (ATTNEAVE 1954). This is possible because, as a result of a long evolutionary history, these Gestalt principles represent implicit expectations of the perceptual apparatus concerning the regularities of the world. These regularities, or redundancies, are not – as such – in the world itself, but imposed by the perceiving system, or, as METZGER (1954) puts it: "Gestalt laws are the general aprioric conditions to make possible the experience of unity, diversity, and form, in KANT's sense" (see KANT 1781). In order to perceive an organized world, the perceptual system creates information and reduces information as aspects of the same process, which is obviously designed to help us obtain an understanding of the world. This "understanding" is always "for us", i.e., adapted to our needs and behavioral options as organisms and human beings.

This view of Gestalt factors emphasizes their fundamental role in "pure" perception. However, psychologists in the Gestaltist tradition have claimed that Gestalt factors are also of importance when it comes to understanding tendencies and performance in human activity, be it in productive thinking, in arts, in shaping personality or in social phenomena. What about the role of Gestalt factors in self-performed human voluntary movements? One may, first of all, plausibly claim that perception of self-performed movements follows the same principles of the perception of movements in general (KÖHLER 1933). There may also be a tendency towards producing "good Gestalts" in the planning and anticipatory imagery of movements. VOGT (1988), for example, suggests a possible role of produced and perceived oscillations in achieving "good Gestalts" in periodic movement performance ("motorische Prägnanz"). In his view however, the production of oscillations in human movements is not necessarily guided by perception and anticipation but might instead be the outcome of autonomic motor processes, which are possibly in part "self-organized". METZGER (1965, 1969), in his "cybernetic" approach, suggested that the intended perceptual course of a movement – and thus, at least indirectly, Gestalt factors – is involved in the actual control of performance ("Führung durch Bewegungsabsicht").

[1] This paper earned the 2nd prize in the Wolfgang Metzger Award 2002 for significant contribution to Gestalt theory. All figures: Copyright Nature, London.

The present paper explores the role of perceptual and anticipatory representations, and Gestalt factors in particular, in human movement performance. A class of apparently simple movements is considered here, namely bimanual oscillations. Movements of this kind include, for instance, periodic wiggling of both index fingers (KELSO 1984), and the continuous circling of both hands (SEMJEN et al. 1995), among others. In the last two decades, such oscillatory movements have been a major focus of studies addressing the basic organizational principles of human movements. Of special interest here is the tendency of the limbs in motion to mutually adjust and harmonize their movement characteristics: When a person moves his or her hands simultaneously there is an inclination towards synchronization in space and time. Especially with higher movement speed there is a strong tendency to move the limbs in mirror-symmetry with regard to the body's sagittal midline.

The symmetry tendency in bimanual movements

A classical paradigm in this regard is the bimanual finger oscillation paradigm introduced by COHEN (1971) and KELSO (1981, 1984) (see Figure 1).

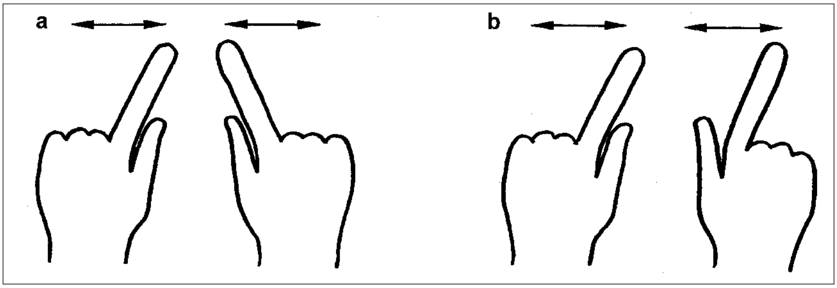

FIGURE 1: Instructed synchronous finger oscillation patterns. Symmetrical movements (a), and parallel movements (b). Reprinted by permission from Nature 414: 69 copyright 2001 Macmillan Publishers Ltd.

A person places his or her hands in parallel on a table and stretches out both index fingers so that they point away from the body. The person is instructed to periodically move both index fingers in a transverse plane, paced by a metronome pulse. At moderate frequencies, only two finger oscillation patterns are stable:(i) oscillations in mirror symmetry to the sagittal midline, and (ii) parallel oscillations. As oscillation frequencies increase, a symmetrical pattern remains stable up to the highest possible movement speed. In contrast, increasing oscillation frequencies heavily corrupt a parallel pattern. Often times a spontaneous, involuntary transition into a symmetrical pattern is observed. Transitions from instructed symmetry into a parallel pattern do not occur. A strong symmetry tendency of this kind is also evident in a wide variety of other bimanual oscillation models such as bimanual circling (CARSON et al. 1997; SEMJEN et al. 1995) and bimanual hand pronation and supination (BYBLOW et al. 1994), among others (see CARSON 1993 for a review). These impressive coordination and stability phenomena, and in particular, the symmetry tendency, have inspired a lively realm of research activities and stimulated the development of the synergetic or dynamic systems approach to movement understanding (HAKEN et al. 1985).

Symmetry is a particularly salient perceptual property. Symmetrical figures are considered "good Gestalts" par excellence providing paradigmatic evidence that there is a "Prägnanzprinzip" guiding form perception. Symmetry perception is a prominent topic in vision research (for a review see WAGEMANS 1997). Therefore it is very surprising that the symmetry tendency in bimanual movements has rarely been considered to be a tendency towards spatial mirror-symmetry, and thus maybe towards a perceptual "good Gestalt". Instead, it has been viewed as a tendency towards co-activation of homologous muscles, probably originating in motoric neuronal structures (CARSON et al. 2000; CATTAERT et al. 1999; HEUER 1993; KELSO 1984; SWINNEN et al. 1997).

Motoric approaches to human movement understanding

A "motoric" interpretation of the symmetry tendency is well in line with a long-standing, still dominant, tradition of "motoric" approaches to human movement understanding, i.e., with the widely-held notion that movements are basically organized by way of coordinative processes in motoric neuronal structures (e.g., JORDAN 1995; KEELE 1968; SCHMIDT 1975, 1982a, 1982b). Some theorists have proposed, for example, that the symmetry tendency originates in bilateral neuronal crosstalk (CATTAERT et al. 1999). Others have proposed that there might be a mechanism that eases motor programming by taking advantage of homologies (HEUER 1993). Needless to say, perceptual rules – Gestalt factors in particular – are unsuitable for understanding the emergence of such a purely motoric phenomenon if the code is in terms of efferent signals. These signals are not part of mental life, so-to-say, but constitute a different level (PRINZ 1984). In any case, there remains a problem of translating muscular activation patterns into the planned perceptual effects of a movement, and vice versa. It has often been emphasized that muscular activation patterns seem not to be perceivable as such. Thus an efferent explanation of this kind initially seems rather plausible, which implies that perception and perceptual anticipation, particularly perceptual Gestalt factors, are not directly responsible for the structure of such muscular activation patterns.

There are theorists who claim that the problem of motor control is basically the problem of organizing the appropriate muscular activation pattern. From this point of view it is muscular activation patterns, possibly in terms of motor commands, which are planned, executed, and stored in memory. These motor patterns are clearly not perceptual in nature. According to this view, the role of the perceptual-cognitive level is only indirect. Let us consider how SCHMIDT (1975, 1982a, 1982b), in his classical, and paradigmatic, theory of generalized motor programs, characterizes the role of perceptual representations of one's own movements. SCHMIDT proposes an action-perception loop of the following kind. The first step in bringing about a voluntary bodily movement is to plan it by way of imagining, or anticipating desired perceptual movement effects. In a second step, this anticipated perceptual outcome is translated into a motor program, i.e., into a coherent representation of the movement in terms of the detailed pattern of the appropriate neuronal commands to the muscles (this translation solves the so-called "inverse problem"). In a third step, the motor program is set into action, i.e., the coherent pattern of motoric neuronal commands is executed. The neuronal commands activate the respective muscles, thus launching the bodily movement (the translation of the neuronal motor program into bodily action solves the so-called "forward problem"). The resulting movement effects are then perceived as "feedback", which is compared with the originally intended movement effects. In the case of a mismatch, corrections are made with regard to the motor program or the inverse and forward translations ("motor schemata"). As a result, the next movement may be performed more correctly.

According to the motoric viewpoint, the crucial, and causal, step in launching a voluntary movement is setting the neuronal motor program into action. Note that – according to this view – organization and coordination of a movement means, basically, organization and coordination of the corresponding motor program. To emphasize again, the motor program is considered to be a coherent, and autonomous, motoric representation of the movement, which is not accessible to phenomenological experience. The organizational principles are special for the motor system, without any obvious role for Gestalt factors or the like. SCHMIDT proposes, that the motoric movement code represents a specification of the relevant muscles, or roles of muscles, and a set of crucial muscular activation parameters. Some of them can be stored permanently as part of the generalized motor program, whereas some of them are flexibly tuned according to the respective situational goals. Relative activation time and relative force of the muscles are considered fixed parameters of the permanent kind whereas absolute duration and force are variable parameters of the flexible kind.

No role for Gestalt factors in "motoric" codes

For our porposes it is important to note three things: (i) the grouping principle of muscles, or of the respective motoric neuronal commands, is almost purely summative. Even if one assumes that hierarchical groupings of muscular synergies are possible, this will not alter the general scheme; (ii) it follows that the perceptual-cognitive architecture of the phenomenological movement, including its meaning and intention, is not present in the motor program; (iii) as there is no obvious capacity limitation, motor programs are not bounded in content, and thus may account for bringing about movements of any degree of formal complexity, even if they involve utterly complicated contraction patterns of a huge many synchronously active muscles.

These principal characteristics are still present also in more recent "motoric" approaches to understanding human voluntary movements (see JORDAN 1995). As mentioned above, proponents of "motoric" approaches often implicitly or explicitly hold that it is most important to understand the translation of the planned body movement into the respective muscular activation pattern, and vice versa, in order to understand how voluntary movements are brought about. In this view, movement control is said to be brought about by way of a "sensory-motor mapping", a "translation", or "coordinate transformation" from sensory into motoric information codes and vice versa (e.g., PELLIONISZ & LLINÁS 1979, 1980; see also CHURCHLAND 1986). As JORDAN (1995) puts it, "sensory and motoric data ... may refer to the same entities but in different coordinate systems. Transformations between these coordinate systems allow sensory and motoric data to be related, closing the sensory-motor loop."

The problem of inverse and forward translation, posed herewith, is not easy to solve in such a framework. One has to ask how planned movement effects are translated into motor programs, and vice versa.

METZGER (1965) illustrates this problem by pointing out that a voluntary movement of the hand, which is experienced as clearly hand-focused, corresponds to a complex innervation pattern of muscles in the upper arm and shoulder. While holding that the mentally anticipated movement ("Bewegungsabsicht") is continuously guiding the physical movement, he has no choice but to state that the transformation of this mental representation into the real movement is "a wonder". PRINZ (1984) emphasizes the conceptual and functional separation of "perceptual codes" and "motoric codes", which are treated as almost incompatible in traditional cognitive psychology and movement science. He claims that the mutual "translation" of these codes into each other can, in frameworks of the kind, only be a result of learned associations of motoric and sensory representations. As there is no structural compatibility of the codes, the motoric and perceptual-cognitive levels are simply "connected" in an associative way.

The role of perceptual representations in motor control according to this kind of motoric approach is clear: perceptual representations in movement anticipation and movement perception (e.g. feedback) are used for comparing the intended movement with the real outcome. In this view, there is no necessity of the perceptual movement representation to be directly functional in controlling muscular activity. In consequence, principles of the Gestalt kind, which may guide anticipation and perception of movements, do not have a functional role in movement execution.

Movement organization might be purely perceptual-cognitive: the common coding approach to perception and action

In this paper, I will favor an alternative approach to understanding human voluntary movements. In contrast to the traditional "motoric" view, the approach suggested here denies the existence of any coherent, integrated, and autonomous representation in terms of a motoric code as separated from perception. Instead I suggest a basic functional role of perceptual representations and, in particular, Gestalt factors, in movement organization and execution. PRINZ (1984) considers the possibility that there might not be a mere associative "connection" between sensory and motoric codes, but instead there is a meaningful "match" – in the sense, that sensory and motoric information is brought together in a functionally meaningful way. According to PRINZ, it remains to be determined how this matching process might work exactly in order to make the body actually move. In any case, in order to meet on a meaningful level, there must be a common representational medium, or "common code", for sensory and motoric information (PRINZ 1984, 1990, 1997). Such a common representational medium, which can only be perceptual-cognitive in nature, seems plausible in the light of manifold experiments (for a review see HOMMEL et al. 2001).

According to PRINZ, the common coding principle implies that perceptual representations not only guide but control movement execution. Interestingly, this claim matches METZGER's (1969) proposal that the "phenomenal-perceptual field" may be functional as a "central steering mechanism". If so, how might this work? HOMMEL (1998) called the suggested action-controlling perceptual representations "event files", in analogy to the notion of "object files" as proposed by KAHNEMANN & TREISMAN (1984; KAHNEMANN et al. 1992). HOMMEL did so because intended, executed, and perceived actions are said to be represented in a similar way for the perceptual representational medium – namely they should be perceived as events. However, in this notion there is no idea, so far, how such "events" might be brought about. Indeed, this problem has not been seriously and convincingly addressed by the proponents of the "common coding" approach, apart from their plausible claim that human movements are brought about, somehow, by way of event files.

Perceptual Gestalt factors might be functional in movement execution

If the theory of common coding is correct, which means that there is a solution to the translation problem, it has to be proposed that event files contain information that is directly functional for movement execution. This is because the economic organization of the movement, as well as the muscular activation, has to be controlled by way of the event file. Certainly, situational features that are connected to the to-be-performed movement are of relevance here, even if only connected by way of simple associative learning (ELSNER 1999). However, taking the common coding approach seriously means that these associations are not established between perceptual and some hidden motoric representations of the kind sketched above. Instead they are forming and structuring the event file itself, i.e., taking place between perceptual features of the situation and perceptual features of the to-be-executed movement.

Specifically: I assume that the event file serves at least two different functions in voluntary movement organization, maybe by way of different kinds of contents. First, the event file exposes how a movement, as embedded in the given situation, "should" look, feel and sound, how it "actually" looks, feels, and sounds, and so on. This is equally assumed in motoric approaches to human movement understanding. Second, there are constituents of the event file, which are directly functional in making the body move. Such a claim is a theoretical necessity in the perceptual-cognitive approach suggested here, whereas in a motoric approach there is no need at all of perceptual elements being directly functional in movement execution.

The event file is possibly limited in content due to limited working memory. This capacity limitation makes vital a most economical organization. This problem does not arise in the traditional motoric representations, as they are conceived as unaffected by capacity limits. This is not a trivial problem. The plausibility of a perceptual approach to human movement organization is very dependent on whether a framework can be presented to account for how (formally) complex patterns of body movements can be coordinated in spite of a limited working memory capacity.

What kind of event file content, or mental activity, might be functional in movement control? METZGER (1982) gives a hint by saying that there might be Gestalt principles that are useful for movement execution. He names the example of "swing" ("Schwung") as a "new" principle, which he claims to play virtually no role in pure perception, but to be of importance in the performance of well-organized movements. What is swing? "Objectively", it means making use of kinetic energy, possibly in order to optimize energy economy of movements. "Swing" may also serve to economically coordinate many body parts by way of a common rhythm, or to organize the movement in a way that the center of gravity moves according to a minimum-jerk principle. Interestingly, there is a strong subjective phenomenal counterpart of how it feels to move with a good "swing". Swing can thus be perceived. Making optimal use of "swing" can be learned. Performance can be adjusted by way of adjusting the corresponding perceptual quality of the swing. To sum up, swing is not only a physical but also a phenomenological quality. This quality is connected, for instance, with the experience of performance pleasure and "flow" (CSIKSZENTMIHALYI & CSIKSZENTMIHALYI 1988).

These considerations are preliminary and do not explain in detail the role of perceptual swing for guiding and directly controlling movements. However, in my view, the example of swing suggests that it is rather plausible to assume a functional role for Gestalt factors in movement control. To infer from the example of swing, such factors can be presumed to bring about a special kind of perceptual experience: Whereas classical Gestalt factors mediate a mere "passive" perceptual experience of the world, these movement-related factors mediate action, or the perception of being active, so-to-say. Their main evolutionary raison d'être might be for the planning and controlling one's own activity. Maybe they are crucial in forming the sense of being active, or even in forming the bodily self, i.e., in forming the fundamental awareness of being an effective actor in a scene. Interestingly, master teachers often maintain that optimizing swing is a major issue in acquiring advanced motor skills such as in skiing or playing the violin (e.g., McCLUGGAE 1983; MENUHIN 1971).

Incidentally, it is not necessary to follow METZGER (1982) in assuming that Gestalt factors of this kind play no role in "pure" perception of the outer world. To maintain the example, one may perceive "swing" while watching a champion make a perfect ski run, while listening to a lively piece of music, or even while looking at a picture painted in wild brush strokes. It is possible that the perception of swing often or always goes along with a resonating experience of one's own activity, but I do not want to insist on this at this early point. It is tempting to speculate that Gestalt factors of this kind easily and naturally mediate movement imitation, conjoint movements in dancing, and the like.

The traditional notion that movements are basically coordinated in the motor system implies a limited functional role of perceptual factors in actual movement control. Maybe in the end a mixed approach will turn out to be the most adequate.

However, as explained below, I am personally much more inclined to a purely perceptual-cognitive approach saying that movements are functionally controlled solely by way of event files. If this is the case, Gestalt factors certainly play a crucial, canonical, role in making the body move. Gestalt factors might mediate the connection between phenomenal content and physical movement.

Evidence supporting a motoric approach to movement understanding is ambiguous

Is there any experimental evidence that the proposed perceptual-cognitive approach to movement control is plausible? Upon reviewing the literature on human movement control one gets the strong impression, at first sight, that the answer is clearly "no". It is widely almost taken for granted that a "motoric" approach is adequate. With regard to spontaneous coordination phenomena, it is often held that there is convincing or even "overwhelming" (CARSON et al. 2000) evidence that phenomena such as the symmetry tendency in bimanual movements originate in motoric neuronal structures (e.g., CATTAERT et al. 1999; HEUER 1993; KELSO 1995; SWINNEN et al. 1997, 1998).

On further examination, however, it seems fair to say that the experimental results, which are often cited to provide evidence for a dominant role of motoric processes in movement coordination, are virtually always open to a perceptual interpretation as well. Following a thorough review of the literature, I am not aware of any result that might not easily be explained in terms of a purely cognitive and perceptual control of the respective movement phenomenon (see MECHSNER 2003; MECHSNER et al. 2001). Quite astonishingly, many authors seem to favor a priori a motoric explanation in cases where both a motoric and a perceptual explanation are possible. Often they do so without even considering that a perceptual explanation might be equally conceivable. In one striking example, it is widely held that the symmetry tendency in bimanual movements reveals a tendency towards co-activation of homologous muscles (e.g., SWINNEN et al. 1997, 1998). This is done in spite of the obvious fact that co-activation of homologous muscles is confounded with spatial, perceptual symmetry of the movement pattern.

Regarding motor programs, the reported theoretical and empirical evidence in favor of complex motoric representations is not unequivocal. The classical argument for the view that complex motor programs are indispensable in motor control may be seriously doubted. KEELE (1968) refers to so-called ballistic movements, which are performed so quickly that an online control via feedback would not be possible. Therefore, according to KEELE, there must be a motoric representation specifying in advance the muscular contraction pattern. However, it is equally plausible to assume that suitable forward and backward mappings in a cognitive and perceptual functional medium are fully sufficient to enable humans to perform even ballistic movements. After all, such movements are usually embedded in ongoing motor activity which ensures a reasonably accurate pre-specification of the relevant movement control parameters using sensory anticipation, which is a continuation in this case. To cut a long argumentation short, a purely cognitive and perceptual approach to understanding human movement organization seems possible, in the light of the available evidence.

A perceptual-cognitive approach to understanding movement is plausible

Is a perceptual-cognitive approach to understanding movement plausible? First, consider the spontaneous symmetry tendency in bimanual coordination. As has been pointed out above, the evidence in the literature is open to a motoric as well as to a perceptual interpretation. Recent experiments by MECHSNER et al. (2001), however, provide strong evidence suggesting that the symmetry tendency is actually perceptual, and not motoric, in nature. In one of their experiments, MECHSNER et al. replicated KELSO's (1984) classical demonstration of the symmetry tendency in the finger oscillation model as described above. MECHSNER et al. (2001) varied this paradigm in a particular way. Similar to the classical model, participants were instructed to periodically move their index fingers in parallel, as well as in symmetry. In a trial, a metronome pulse paced the oscillation frequency from 1.4 Hz up to 3.6 Hz, over the course of 24 s. As a newly introduced additional condition, the hands were individually placed palm-up or palm-down (Figure 2). Positions with both hands either palm-up or palm-down are called "congruous". Positions with one hand palm-up and the other palm-down are called "incongruous."

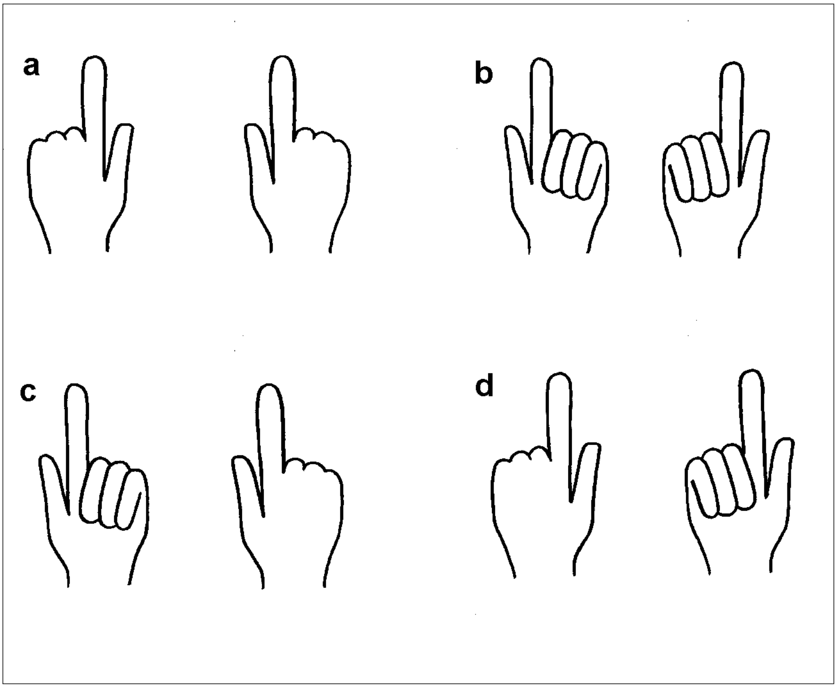

FIGURE 2: Instructed palm positions. Congruous positions with both palms down (a) or both palms up (b). Incongruous positions with one palm up and the other palm down (c, d). Reprinted by permission from Nature 414: 69 copyright 2001 Macmillan Publishers Ltd.

With a congruous palm position, a stability advantage of the symmetrical pattern as well as a tendency towards symmetry was expected, as in KELSO's (1984) results. This was so because here, as in KELSO's original experiment, symmetrical finger oscillation goes together with periodic co-activation of homologous muscle groups. The interesting condition concerned the incongruous palm positions, because here only the parallel movement mode may involve periodic co-activation of homologous muscle groups. If there is actually a tendency towards a co-activation of homologous muscles, then the parallel movement mode should be more stable than the symmetric mode. On the other hand, if there is a tendency towards spatial, and thus perceptual, mirror-symmetry, then the symmetric movement mode should be more stable than the parallel mode, even though non-homologous muscle groups are periodically co-activated.

The findings by MECHSNER et al. (2001) were straightforward. With congruous as well as incongruous palm positions, the mirror-symmetrical movement pattern was more stable than the parallel pattern. Independent of palm positions, spontaneous transitions from an instructed parallel movement into symmetry were observed at increasing oscillation frequencies, but not into the reverse direction. The same outcome was revealed if the participants' view was occluded, thus perception of the hands was restricted to proprioception. MECHSNER et al. concluded that the symmetry tendency is biased towards spatial, perceptual symmetry, without any regard to the involved muscles, or to the corresponding neuronal commands.

This is a challenging result. To be fair, it has been known before that processes in the perceptual functional medium can be powerful enough to bring about spontaneous movement coordination phenomena. For instance, two participants looking at each other will tend to synchronize swinging limbs as well as swinging pendulums (SCHMIDT et al. 1990,1998; SCHMIDT & O'BRIEN 1997). Even spontaneous transitions from parallel into symmetrical movements occur. Intrapersonal oscillations of one hand and one foot tend to adopt a parallel oscillation pattern, independent of a prone or supine position of the forearm (BALDISSERA et al. 1982). Manipulation of haptic feedback can stabilize, but also reverse the preferred coordination pattern in a finger flexion and extension task (KELSO et al. 2001). Such evidence notwithstanding it has been argued that intrapersonal coupling of homologous limbs is a special case (e.g., SWINNEN et al. 1998), as coupling of homologous muscles is possible here, and indeed the reason for the symmetry tendency. Until now, there has been no evidence against this common claim.

MECHSNER et al.'s (2001) results on finger oscillation demonstrate that there is reason to doubt the role of motoric constraints in bringing about the symmetry tendency. Instead, one may plausibly hypothesize that this tendency is purely perceptual in nature. Confirming results were obtained in the case of a bimanual four-finger tapping model (MECHSNER et al. 2001), as well as in a bimanual wrist oscillation model (MECHSNER et al., submitted). It is worth noting that it seems to be no problem to instantaneously organize the suitable muscular activity that corresponds to the perceptual tendency. The suitable motoric neuronal commands seem to be automatically selected and tuned in, always adapted to the perceptual movement goal.

One may speculate that not only spontaneous but also voluntary movement patterns are coordinated directly by way of perceptions and perceptual anticipations, whereas corresponding coordinative processes in the motor system are not at all necessary. In all fairness, in saying so I certainly acknowledge that there are complex patterns of muscular activity and motoric commands that bring about the movements. However, I assume that such a pattern is not an autonomous entity, which is conceived as such and well organized in and of itself. I rather assume that this pattern is organized as a by-product of ongoing processes in a perceptual functional medium. Compare the motor system to a piano, movements to ongoing music, and the player to the perceptual-cognitive system. In order to produce music it is possible to make use of a player piano or electronic equipment that produces rhythms, harmonies, or even produces fully arranged melodies. On the other hand, one may play a normal piano. In this case the complex activity inside the apparatus is not due to the complexity of an autonomous internal configuration, but instead is fully dependent on what the player is doing. I am much inclined to hypothesize that the motor system does not work like a player piano, thus its activity is fully dependent on what is going on in the cognitive and perceptual functional medium.

An experiment on bimanual circling by MECHSNER et al. (2001) provides additional evidence. Participants circled two visible flags by way of two cranks, which were hidden under the table (Figure 3a). The left flag circled directly above the left crank and hand, i.e., in exact spatio-temporal correspondence to the hand. The right flag, however, circled in a 4:3 frequency relationship with regard to the right crank and hand, due to a gear system.

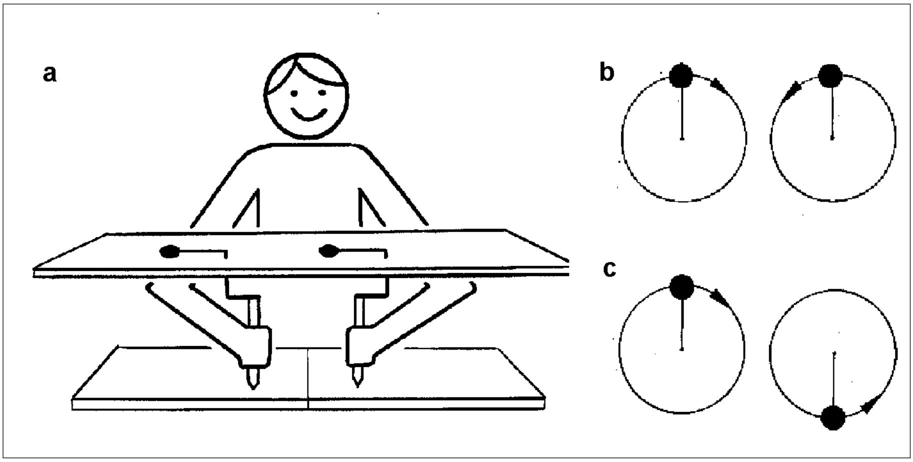

FIGURE 3: Flag circling apparatus (a) (see text). Instructed flag movement patters. Mirror-symmetry (b). Antiphase (c). Reprinted by permission from Nature 414: 71 copyright 2001 Macmillan Publishers Ltd.

After twenty minutes of training, primarily with the handling of the right flag, the participants were instructed to circle the visible flags inwards either in mirror-symmetry or in antiphase (see Figure 3b,c). They were asked to begin at a slow, comfortable velocity and then speed up to a velocity they considered fast, but not beyond the point they lost visual control. In order to perform the task, participants had to circle their hidden hands in a 4:3 frequency relationship. Two peculiarities are worth noting here. First, the circling pattern of the flags cannot be inferred, or predicted, from the circling pattern of the hands. Second, it is virtually impossible for naive subjects to perform bimanual movements with a 4:3 frequency relationship when instructed to do so (see KELSO 1995). In consequence, no body-oriented strategy is possible in order to bring about symmetry or antiphase in the flags. This means, there are certainly no body-oriented motor programs whose performance brings about the intended flag circling patterns. If participants are able at all to perform the instructed patterns, then it is due to perceptual-cognitive strategies.

The results were clear: participants managed to perform symmetric as well as antiphase flag circling patterns at circling frequencies up to about 1.5 Hz. The symmetric pattern was much more stable than the antiphase pattern. With increasing circling speed, transitions from an instructed antiphase pattern into a symmetrical pattern were obvious, but not vice versa.

These results demonstrate that perceptual strategies are well suited, and indeed sufficient, to effectively bring about symmetric as well as antiphase circling patterns. A "motoric" representation of the to be performed movement pattern is not at all needed. Most interestingly, the body movement can be of an uttermost formal complexity when performed in order to achieve a simple movement effect.

I hypothesize that this result can be generalized, i.e., that a purely perceptual-anticipatory coordination of both spontaneous as well as voluntary movement patterns is rather plausible. Such a perceptual-cognitive conception of human movement organization is in stark contrast to the widespread notion that the basic coordination of movements is done in a motoric functional medium, which is not accessible to phenomenological experience. However, the notion of a perceptual-anticipatory organization of movement is not new. The perceptual-cognitive approach to movement control means a renaissance and revitalization of classic ideas, such as the "ideomotor" approach put forward by JAMES (1890), or the model-theoretical studies presented by BERNSTEIN (1967). Actually, this perspective has never been truly silent, although it seems to have been forgotten by researchers who favour motoric approaches. Now, as the strong limitations of these approaches become more and more obvious, it seems as though a perceptual-cognitive framework might well overcome these limitations. As reported above, there are several sophisticated "motoric" theories of movement planning, learning and performance. In order to develop an alternative perceptual-cognitive theory, it remains to be explored how the perceptual organization of movements might be accomplished. This is true of both the intended result of the movement, as well the actual body movements that have to be performed.

Gestalt factors

For the bimanual movements considered here, the intended result of the movement is to perform the instructed pattern with the fingers or with the flags. The respective effectors may be coupled, for example, by common straightness and curvature characteristics, parallel or symmetric direction. It is well known that certain common perceptual characteristics in the effectors may ease performance (e.g., SWINNEN et al. 1997, 1998). Moreover, it has been revealed that synchronous movements of both hands are particularly well performed when they complete each other into a well-perceptible whole, or “good Gestalt” (FRANZ et al. 1998). Motoric approaches as conceived so far are only able to explain an intrapersonal symmetry advantage (for an additional claim, see CARSON et al. 2000). A perceptual-cognitive approach should, in principle, be able to explain intrapersonal, interpersonal as well as person-object or person-environment coordination tendencies of many kinds in a common framework.

Let us consider the symmetry advantage in more depth. If the symmetry tendency is actually purely perceptual in nature, its explanation has to rely on processes in a perceptual functional medium only, without regard to the involved muscles and motoric neuronal commands. When considering why there is a particularly strong perceptual symmetry tendency, Gestalt factors quite naturally come to mind. After all, symmetry makes a “good Gestalt” par excellence. However, it is not quite clear whether this is a sufficient explanation of the symmetry advantage and tendency.

WAGEMANS (1997) reviews the literature on symmetry detection in the human visual system. He names a wide variety of factors, which are involved or might be involved in the perception of symmetry, and in particular, of mirror-symmetry. Symmetry means, in a broader sense, self-similarity of a pattern under a class of transformations, namely translations, rotations and reflections. Given this definition, it is not obvious why mirror-symmetry should be a special case. However, stimuli that are mirror-symmetric (i.e. with regard to a vertical line passing through the point of eye fixation) are detected much more effortlessly, rapidly and spontaneously than corresponding figures, which are rotational-symmetric or translational-symmetric, or mirror-symmetric with regard to a sloping line. It seems to be a peculiarity of our perceptual system to work in this way. However, the preference for mirror-symmetry is not, or at least not completely, a result of the bilateral symmetrical structure of the central nervous system. It rather seems to emerge due to the working of a more general apparatus that detects regularities.

In the detection of mirror-symmetry in visual patterns, the elements closest to the symmetry axis are of major relevance. Also, elements near the edges of the pattern are important to the percept. Of interest, mirror-symmetry seems to be a perceptual property that tends to be exaggerated by the visual system, even under surprisingly large distortions. Theoretical and computational models of visual symmetry detection must include strategies for embedding the pattern into a suitable frame of reference as well as strategies for successive grouping of pattern elements and features. For more information and theoretical accounts, we refer the reader to the paper by WAGEMANS (1997).

Symmetry detection in movements has not been as thoroughly investigated as symmetry detection in static patterns. It seems plausible to assume that symmetry in movements is perceived if the respective synchronous movements are symmetrical. It is not sufficient that the movement traces are spatially symmetrical. The crucial, determining, factor is the synchronous symmetry of the moving effectors, with regard to the respective loci as well as to the respective movement directions and velocities.

Is the ease of perceptual symmetry detection the reason why symmetrical movements are performed so easily? In a series of experiments, BINGHAM et al. (1999, 2001) addressed this question by investigating the quality of perception of the relative phase of two oscillating objects. They found a clear perceptual advantage for symmetrical – particularly mirror-symmetrical – patterns. For example, observers judged that relative phase variability was lower for symmetrical than for unsymmetrical patterns, even though the variability was constant. Also, an increase in oscillation frequency yielded an increase in perceived variability at all mean relative phases, unless the there was symmetry. One may infer from these results that a symmetrical movement pattern of oscillating objects is more precisely perceived than other relative phases.

If movements are self-performed, they are not only perceived visually, but also by kinesthetic proprioception. The constant presence of this additional modality may, in itself, make a difference concerning perception of one's own movement. Imagine, for instance, a case where the hands are placed far enough apart that a synchronous view is impossible, or that they are behind the back. As a result of proprioception, both hands are easily perceived synchronously in their spatio-temporal relationship, and their actions can synchronously be controlled.

Perceptual strategies in bimanual movement performance

It is possible that the relevant type of information used, or produced, for movement control is of the same categorical kind for both kinesthetic and visual control. For example, "swing" ("Schwung") can be perceived visually and kinesthetically. "Swing" is obviously used in kinesthetic movement control and might play a role in visual movement control as well. Think of a model car race where the cars are skillfully driven under visual control only.

What kind of perceptual control strategy is relevant in the performance of symmetric bimanual movements? Naively one may assume that the participant would try to continuously move the effectors in mirror-symmetry. However this does not seem to be the way people actually perform symmetrical movements. To get some hints concerning the actual strategies, we asked subjects who participated in our bimanual circling experiment how they performed the instructed movement patterns.

Even at comfortable circling speed, when symmetry as well as antiphase can easily be maintained, most participants judged symmetry to be much easier to perform than antiphase. When asked to explain why symmetry is easier than antiphase, they usually report something like: "In order to perform a symmetrical pattern I simply took care that the flags periodically met in the middle. In order to perform antiphase, I tried to periodically repeat the pattern where one flag passed North exactly at the point in time when the other flag passed South." These are clearly strategies aimed at repeating well-defined perceptual patterns. It is intuitively plausible that the second strategy is more demanding than the first one.

Note that the focus of the reported strategies is not so much the intended form of the movement (e.g., "mirror-symmetrical circling"), but perceptual characteristics, which are used in order to better control the movement. In fact, the reported strategy of symmetry control often leads to a distortion of the exact mirror-symmetrical pattern: observers maintain the correct spatial relationship of the flags at the meeting point, whereas the rest of the trajectories are more variable.

It must be noted, however, that the "central point strategy", including the accompanying trajectory distortions, seems much more pronounced in the flag-circling task than in the hand-circling task. This may be so because the flags can only be controlled visually, which means that their spatial relationship is especially well perceived when the flags meet in the middle. In comparison, kinesthetic perception of the hands may still be rather good if the hands are somewhat apart from each other though they can not so well be seen any more.

It still has to be investigated whether participants actually behave in the way they report. However, it seems plausible, so far, that the perceived difficulty of a movement pattern is revealing the difficulty of the particular perceptual strategy used, and not a difficulty caused by whether one has to conform or to oppose distinct tendencies of a motoric origin. It may well be that it is not so much the symmetry as such but rather the specific control strategies used which makes performance of symmetry so easy.

Intention as an organizing principle in human movements

Let us consider the factor of "swing" a little more in depth. To this point, we considered a skillful swing, loosely speaking, as an aptly timed impulse allowing the optimal use of induced kinetic energy. Taken as such, a skillful swing seems to fulfill an optimality criterion for moving in the most economical way with minimum energy expenditure. The degree of attained optimality in this regard has a clear counterpart in the experienced movement quality. Thus one may plausibly suggest that swing is a Gestalt criterion especially tailored for movement control. However, a most important dimension of swing is still lacking in our considerations: swing is only optimal when the movement goal is actually achieved. We have been considering swing as a causal structure, but we must also consider its final, or teleonomic, structure. The basic characteristic of our body movements is intentionality, i.e., loosely speaking, goal-orientedness. It is the always present intentionality of our body movements, which makes them "Gestalten" much different from object movements.

According to MERLEAU-PONTY (1945), bodily movements reveal the intentional structure of phenomenological space. Voluntary movements are "wholes" as, from the beginning, they pursue and reveal an intention. For instance, in a grasping movement the starting hand is already unified with the intended object to-be-grasped. The difference between the actual hand position and the intended hand position is experienced as a "tension" or "polarity" between hand and object. Intentional phenomenal space, and thus movement space, is structured by polarities of this kind. In analogy to potential fields in physics, one may rightly speak of phenomenal fields. Much like physical fields, phenomenal fields are structured by attraction and repulsion centers (LEWIN 1936; METZGER 1969).

By considering the bodily pole in the phenomenological field, MERLAU-PONTY (1945) explicitly emphasizes a fundamental dimension of "affordance", which is merely implied in GIBSON's (1979) ecological approach to perception. Relying on earlier ideas by LEWIN and KOFFKA, GIBSON suggests that we do not simply apply purely mental categories in order to make sense of the world. Instead, we perceive the world according to possible bodily actions. His term "affordance" is demonstrated by the following peculiarity in perceptual phenomenology: while perceiving the slant of a hill, we implicitly judge the effort of climbing it. BHALLA and PROFITT (2000) revealed that perceived geographical slant increases immediately after a long run in comparison to the slant perceived prior to the beginning such an exhausting bodily exercise. Naively, we consider slant an objective property of the hill. Only now are we beginning to realize that this property is intimately connected to our behavioral options.

However, affordances are not only perceived as properties of the affording object. By way of an educated phenomenological sensitivity we may also experience the specific way our body is related to the objects of our interest. In the hill climbing example, one may vaguely imagine oneself climbing the hill while judging its slant. If so, "affordance" is not only perceived in the object but also in the subject. Since affordance means anticipation and anticipation is basic for intended movements, MERLEAU-PONTY rightly says that the body is not only immanent, like a neutral object, but instead is always immanent and transcendent at once.

The role of affordances in movement control

Polarities in the phenomenal field, which are perceived as affordances, make us move and are fundamental for any voluntary movement experience. In other words, they are fundamental for structuring the phenomenal "figure", which is experienced as the execution of a movement. The idea that anticipated goals are crucial for movement initiation is supported by some new evidence reported by HOMMEL et al. (2002). A movement as a whole is a timed structure as defined and enclosed between the starting point condition (i.e., the intentional polarity of body and object) and the end point condition (i.e. the end state of the body having reached the goal). Much like spatial borders enclose a spatial region, these temporal borders enclose a temporal region.

When considering our described bimanual oscillation models there are no starting and endpoint conditions, nor are there any obvious external goals, such as an apple to be grasped or the like. One might say that the movement is a goal in itself, permanently providing an affordance that is defined by the intention to maintain it. Just as in physics, there are not only fixed point attractors defining a final steady state, but also limit cycle attractors defining a dynamic "state" of permanently ongoing, periodic movements.

There is a second type of affordances not mentioned so far, but typical for movements. These affordances do not define an overall goal of the movement, but are rather constructed by the performer in order to execute the movement well – they are relevant in connection with movement strategies. Take the usual strategy in bimanual mirror-symmetrical circling movements. As reported above, many subjects mainly take care that the circling hands "meet in the middle". This periodically re-occurring transient state thus can be regarded as defining an affordance, namely the movement goal for every cycle. This "strategic" affordance, possibly in combination with others, is thus basic for the spatio-temporal phenomenal field structure of symmetric bimanual circling for those individuals who apply this kind of strategy. Furthermore, it is possible that this affordance is tightly associated with the production and experience of a mental and bodily rhythm.

The detailed characteristics and structure of the affordance to "periodically meet in the middle" remains to be determined. For example, in uni-manual oscillations paced by a metronome there seems to be a tendency to move towards a nearby object on-beat (MECHSNER, unpublished results). Such a tendency would in itself result in a symmetry tendency in bimanual oscillation, as the hands or oscillating fingers are objects. Assumed, periodic movements go with a mental beat, every hand or finger is inclined to go towards its contralateral counterpart along with that beat, and this means a symmetrical oscillation pattern. A tendency of this kind might possibly be generalized by a tendency to structuring movements temporally by way of coupling salient, transient, events, such as reversal points, short-time accelerations, acoustical or optical signals, jerks, close approaches to landmarks, and so on. Much work is still needed in order to work out these problems in detail.

To sum up, movement control might be much more independent of coordination processes in the motor system than previously thought. If so, perceptual factors, and in particular Gestalt factors, are crucial for movement control. The handling of complex motor representations that have to be accurately mapped to the sensory movement outcome would require a complicated and rather inflexible machinery. In contrast, perceptual control as proposed here allows for the planning and performance of movements in a most flexible way, in a free interplay of manifold cognitive and sensory factors.

Summary

A long-standing, still dominant, tradition holds that voluntary movements are basically organized in the motor system, according to principles which are specifically "motoric", in clear separation to processes in a perceptual representational medium such as anticipating and perceiving one's own movements. From the motoric point of view, there is no place for any functional role of Gestalt factors. I will argue against this traditional view. I hypothesize that human voluntary movements are functionally organized and coordinated solely by way of perceptual representations, so-called "event files", without the need for a second, motoric, representation. If so, Gestalt factors might be of basic importance in imagination and perception, as well as for the control strategies used to actually perform voluntary movements.

Zusammenfassung

Traditionell wird oft angenommen, daß menschliche Willkürbewegungen wesentlich im motorischen System koordiniert, gelernt und ausgeführt werden, als wohlorganisierte Muster efferenter Kommandos zu den Muskeln. Die Prinzipien einer derartigen Koordinationsweise sind spezifisch „motorisch", im Unterschied zu den Prinzipien, nach denen kognitive und perzeptuelle Prozesse organisiert werden, etwa die mentale Antizipation von Bewegungen. Gestaltfaktoren spielen bei derart aufgefaßten motorischen Koordinationsprozessen keine funktionale Rolle, denn diese Prozesse werden als summativ und assoziativ verstanden. Ich argumentiere gegen diese Vorstellung und favorisiere stattdessen die Sicht, daß menschliche Willkürbewegungen funktional ausschließlich über perzeptuell-kognitive Repräsentationen organisiert werden, ohne daß dazu eine zweite motorische Repräsentation notwendig ist. Wenn dies so ist, könnten Gestaltfaktoren nicht nur bei der Vorstellung und Wahrnehmung von Bewegungen wesentlich sein, sondern ebenso für die Kontrollstrategien, welche die Bewegungsausführung leiten.

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