Universal Journal of Psychology 2(9): 285-289, 2014
DOI: 10.13189/ujp.2014.020903 http://www.hrpub.org

Interpersonal Distances are the Consequence of the Self-organization of Human Spatial Behavior: A Theoretical Study Based on Synergetics

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Abstract It is well documented that humans position themselves at preferred distances with respect to others. The distances characterizing human spatial behavior are known to depend on the social interactions between the actors and their dyadic partners. A quantitative model that predicts interpersonal distances and is based on the concept of the self-organization of human spatial behavior has been missing in the literature. In the present study such a model is derived within the framework of synergetics, a theory of self-organization. The model corresponds to an evolution equation for the variations of interpersonal distance over time. In line with the equilibrium point hypothesis of interpersonal distances discussed in the literature, preferred distances are represented by the fixed points of the proposed evolution equation. In this context, it is argued that the adjustment of an actor from a personal to an intimate interpersonal distance can be considered as a subcritical pitchfork bifurcation. As a by-product of the proposed theoretical approach, the notion is supported that interpersonal distances are body-scaled.

Keywords Interpersonal Distance, Body-scheme, Self-organization, Subcritical Pitchfork Bifurcation

1 Introduction

A fundamental question in psychology and the neurosciences is whether human behavior is determined by the particular structure and organization of the human body and brain or is determined by so-called first principles that hold not only for humans but also for other systems of the animate and inanimate world. In social psychology, the existence of certain interpersonal distances has been established by experimental research [1, 2]. However, current research does not provide an answer why interpersonal distance as a phenomenon exists at all and whether the phenomenon requires a mechanistic explanation or allows for an explanation in terms of first principles. Research on interpersonal distances has primarily focused on the conditions that affect interpersonal distances [3, 4, 5]. For example, gender effects [6, 7] and body-size effects [8] have been found. Body-size effects provide a hint that interpersonal distances can be understood from a fundamental first principle: the self-organization of perception-action systems [9, 10, 11]. The reason for this is that a key concept in the theory of self-organization is the notion of control parameters. Control parameter in turn are variables that are scaled to various system properties. In the context of human perception and action the scaling might be with respect to body-dimensions [12]. For example, transitions between walking and running are governed by the Froude number which (roughly speaking) measures the locomotion speed of an actor relative to the leg length of the actor [12]. Likewise, in the context of human grasping, a body-scaled parameter (namely, the size of a to-be-grasped object measured in units of the hand size of an actor) has been established as a control parameter governing the transition from one-handed grasping to two-handed grasping [13, 14]. Therefore, in what follows, we will propose a top-down approach to understand the phenomenon of interpersonal distances from the theory of self-organization. In particular, we will show that the experimental observation that preferred interpersonal distances differ for personal and intimate social interactions follows from the principles of self-organizing systems.

2 Synergetic order-parameter model for interpersonal distances

2.1 Function expansion of order-parameter model determined by system constraints

We consider a person (an actor) who is engaged in some form of communication with another person. In particular, the actor will position himself or herself with respect to the other at a preferred interpersonal distance that has the nature of a stable equilibrium point [2]. The act of communicating with the other including the choice of the actor where to position himself or herself in space with respect to the other is assumed to be the product of a self-organization process. The self-organization process is assumed to operate close to bifurcation points [15].

Under these conditions, the principles of synergetics [16], a theory of pattern formation and self-organization, apply. Accordingly, the self-organized patterns can be characterized by an order parameter. In principle, the order parameter can be determined from the underlying neurobiological evolution equations using a mechanistic approach (bottom-up approach) [16]. In practice, the relevant evolution equations are not well known. Even if the relevant evolution equations were given it is not a-priori clear whether explicit analytical expressions can be derived because the problem at hand might be mathematically involved. Therefore, in what follows we will derive an order parameter equation for interpersonal distances using a top-down approach. To this end, we assume that the interpersonal distance y is an appropriate characteristic variable of the postulated self-organization process and can serve as order parameter. The evolution equation of y is the order parameter equation of interest. Stable stationary solutions of the order parameter equation then correspond to predicted preferred interpersonal distances.

We take a classical mechanics point of view and consider y as the relative coordinate between the coordinates of two point particles (the positions of two actors). Therefore, y is a signed distance. If we define y as the difference between the coordinates of actor A and B, then $-y$ is the difference between the coordinates of actors B and A. Assuming identical actors, it follows that solutions of the evolution equation must be invariant with respect to mirror-imaging of the coordinate axis. This is a constraint that will be used below. Furthermore, we note that order parameter equations are typically first-order differential equations [16]. Consequently, we assume that y as function of time t satisfies a differential equation of the form

$$\frac{\mathrm{d}}{\mathrm{d}t} y = f(y) \; . \tag{1}$$

The function $f(y)$ can be considered as a generalized force term that determines the dynamic behavior of the interpersonal distance y.

In order to determine $f(y)$ we need to conduct a series of steps that have previously been conducted for the so-called Haken-Kelso-Bunz model of coordinated movements [17]. These are formal steps that are not specific to the Haken-Kelso-Bunz paradigm but can be conducted for any given problem at hand. First of all, we note that (1) exhibits a potential dynamics like

$$\frac{\mathrm{d}}{\mathrm{d}t} y = -\frac{\mathrm{d}}{\mathrm{d}y} W(y) \; , \; f(y) = -\frac{\mathrm{d}}{\mathrm{d}y} W(y) \; , \tag{2}$$

where W is the potential function related to the generalized force f. Second, we introduce a scaling parameter $L > 0$ that might be measured in meters or centimeters. We then define a scale-free relative distance x by

$$x = \frac{y}{L} \Leftrightarrow y = xL \; . \tag{3}$$

That is, while y is the interpersonal distance in the laboratory space measured in units like meters or centimeters, the variable x is defined on a scale-free space. Both distance measures can be converted into each other like $x \leftrightarrow y$, provided L is given. The dimensionless variable x is a rescaled order parameter. The order parameter equation for x can be derived from (1) and (3):

$$\frac{\mathrm{d}}{\mathrm{d}t} x = \frac{1}{L} \frac{\mathrm{d}}{\mathrm{d}t} y = \frac{f(xL)}{L} \; . \tag{4}$$

To simplify the notation, let us define the force function $g(x) = f(xL)/L$. Equation (4) then becomes

$$\frac{\mathrm{d}}{\mathrm{d}t} x = g(x) \; . \tag{5}$$

Equation (5) again admits for an interpretation in terms of a potential dynamics involving a potential $V(x)$. We have

$$g(x) = -\frac{\mathrm{d}}{\mathrm{d}x} V(x) \Rightarrow \frac{\mathrm{d}}{\mathrm{d}t} x = -\frac{\mathrm{d}}{\mathrm{d}x} V(x) \; . \tag{6}$$

At this stage we determine $V(x)$ using the system constraints of the problem at hand [17]. As mentioned above, solutions of the evolution equation must exhibit a mirror-symmetry property such that if $y(t)$ is a solution then $-y(t)$ is a solution as well. This implies that the potential must be symmetric with respect to $x = 0$. That is, we require

$$V(x) = V(-x) \; . \tag{7}$$

Second, for large distances $x \to \pm\infty$ the interaction between the actors vanishes, which implies that $g(x \to \pm\infty) = 0$. Likewise, we get

$$V(x \to \pm\infty) = \text{const.} \; . \tag{8}$$

The next step is to expand $V(x)$ into a set of functions that satisfy the constraints at hand [17]. In our context, the constraints are given by (7) and (8). The function set that satisfies these two constraints are the symmetric Hermite functions that will be denoted by $V_{k,o}$. Here, the sub-index "o" stands for "original" in order to distinguish between a rescaled version of the functions that will be introduced below. The function expansion reads $V(x) = \sum_{k=1}^{\infty} A_k V_{k,o}(x)$, where A_k are expansion coefficients. In particular, the first three Hermite functions read

$$\begin{aligned} V_{1,o}(x) &= -\exp\left\{-\frac{x^2}{2}\right\} \; , \\ V_{2,o}(x) &= -(4x^2 - 2)\exp\left\{-\frac{x^2}{2}\right\} \; , \\ V_{3,o}(x) &= -(16x^4 - 48x^2 + 12)\exp\left\{-\frac{x^2}{2}\right\} \; . \end{aligned} \tag{9}$$

Note that without loss of generality we have put a minus sign in front of all Hermite functions. The minus signs is chosen such that V_1 is a potential with minimum at $x = 0$. In order to obtain expansion coefficients that are in a similar range it is useful to rescale $V_{k,o}$. To this end, we introduce new functions $V_k = V_{k,o}/Z_k$ such that $|V_k(0)| = 1$. The expansion of the potential function then reads

$$V(x) = \sum_{k=1}^{\infty} B_k V_k(x) \tag{10}$$

with $B_k = A_k/Z_k$. For example, for $k = 1, 2, 3$ we have $Z_1 = 1$, $Z_2 = 2$, $Z_3 = 12$ and

$$\begin{aligned} V_1(x) &= -\exp\left\{-\frac{x^2}{2}\right\} \; , \\ V_2(x) &= -(2x^2 - 1)\exp\left\{-\frac{x^2}{2}\right\} \; , \\ V_3(x) &= -(\frac{4}{3}x^4 - 12x^2 + 1)\exp\left\{-\frac{x^2}{2}\right\} \; . \end{aligned} \tag{11}$$

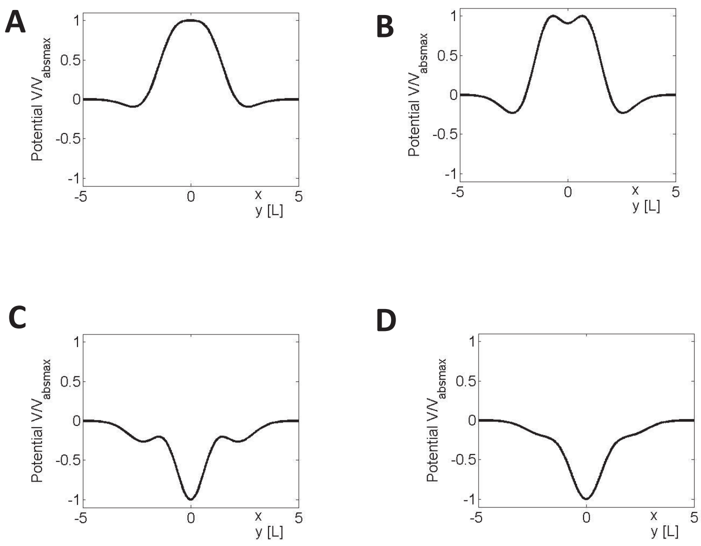

Figure 1. Shape of the potential V as function of the control parameter $\alpha = a/c$. V was computed from (13). On the horizontal axis the rescaled order parameter x is plotted or alternatively the distance y in units of the scaling parameter L is shown. On the vertical axis the ratio V/V_{absmax} is shown, i.e., the potential is rescaled by the maximal value in the amount. Panels A,B,C,D correspond to control parameters $\alpha = -10, -5, 5, 10$.

2.2 Transitions between personal and intimate spaces

We will focus on transitions between personal and intimate spaces. As we will see below, for this purposes it is sufficient to consider a function expansion that contains only the first three terms. Consequently, the truncated order parameter equation model for the order parameter x reads

$$\frac{\mathrm{d}}{\mathrm{d}t}x = -\frac{\mathrm{d}}{\mathrm{d}x}V(x)\ ,\ V(x) = aV_1 + bV_2 + cV_3\ . \qquad (12)$$

The parameters a, b, c are the expansion coefficients of the first three rescaled, symmetric Hermite functions.

We consider next a person who switches from personal space distance to an intimate space distance (we might a person who performs an embracing gesture as part of a greeting or say-good-bye ritual). That is, the proxemic space changes from personal to intimate as a result of a change in the social interaction.

Mathematically speaking, let α denote a parameter that characterizes the social interaction in which an actor is engaged. We will consider α as control parameter and assume for sake of simplicity that it is a real number that might take on positive or negative values. The change in the social interaction from personal to intimate is described by a change of α. More precisely, the control parameter is assumed to pass beyond a critical value of α. As a results, the interpersonal distance changes from $y \approx 0.7$m (personal space) to $y \approx 0$m (intimate space) [1, 2].

Let us determine the bifurcation diagram related to such a change. Since the problem at hand exhibits a mirror-symmetry property, the bifurcation is of the pitchfork type. The order parameter y (or the rescaled counterpart x) is assumed to change discontinuously. Therefore, the pitchfork bifurcation is subcritical. A detailed analysis shows that it is not possible to obtain a subcritical pitchfork bifurcation with the two first expansion function. That is, for $a, b \neq 0$ and $c = 0$ the subcritical case can not be modeled (we will return to an alternative application of the condition $a, b \neq 0$ and $c = 0$ in the discussion section). However, as we will show next, for $a, c \neq 0$ and $b = 0$ a subcritical pitchfork bifurcation can be obtained. Let us put $b = 0$. Equation (12) then becomes

$$\frac{\mathrm{d}}{\mathrm{d}t}x = \frac{\mathrm{d}}{\mathrm{d}x}V(x)\ ,\ V(x) = aV_1 + cV_3\ . \qquad (13)$$

When changing $\alpha = a/c$ with $c > 0$ from $\alpha = a/c = -10$ to $\alpha = a/c = 10$ then the potential $V(x)$ changes qualitatively in form of a subcritical pitchfork bifurcation, see Fig. 1. That is, for relative large negative values of α the order parameter model exhibits only stable fixed points at $x \pm d$ with $d > 0$ (panel A). The value $d > 0$ reflects a preferred interpersonal distance related to the personal space of the actor. At a critical value $\alpha_{c,1}$ a stable fixed at $x = 0$ emerges (panel B) and the order parameter model predicts bistability of personal and intimate space. However, since the fixed point of the personal space is stable the actor will continue to position himself or herself at a personal space distance rather then at the distance of the intimate space. For positive but not too large values of $\alpha = a/c$ the stable fixed point at $x = 0$ reflecting intimate space corresponds to the global maximum of the potential (panel C). The order parameter dynamic is still bistable such that the actor may maintain a position at the personal space distance. However, slight fluctuations will be sufficient to move the actor out of that condition and will bring him or her to the stable fixed point of the global potential maximum that reflects an intimate space distance. In particular, when α becomes larger than a critical value $\alpha_{c,2}$ with $\alpha_{c,2} > \alpha_{c,1}$, then according to the potential dynamics interpretation of the order parameter model (13) the intimate space is the only stable performance pattern.

In Fig. 1 the control parameter was increased in rather large steps. We conducted numerical simulations in order to determine the stable and unstable fixed points for a range of

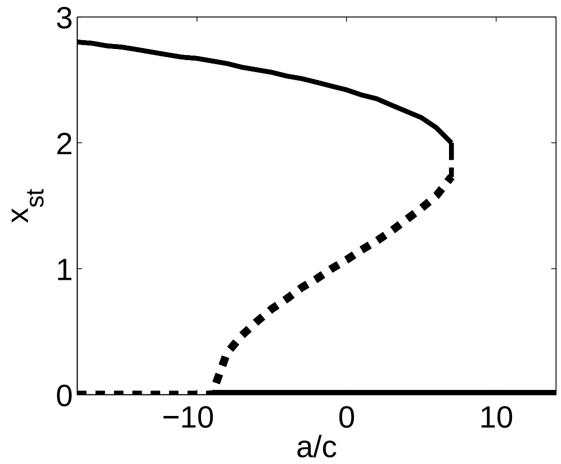

Figure 2. Subcritical pitchfork bifurcation diagram (only the upper half is shown) of the scaled distance order parameter x_{st}. Solid (dashed) lines represent stable (unstable) fixed point locations. See text for details.

control parameters α. This procedure yielded the bifurcation diagram shown in Fig. 2. Figure 2 shows stable and unstable fixed points of the rescaled order parameter x versus α. Only the positive values for x are shown. From the numerical solution method we obtain estimates for critical control parameters: $\alpha_{c,1} \approx -9.0$ and $\alpha_{c,2} \approx 7.0$.

2.3 Laboratory framework and body-scaled model

In order to relate the dimensionless order parameter x with distances y measured in the laboratory frame, we consider the scaling parameter L and the mapping $y = x\,L$. In order to obtain a fixed point for y at $y \approx 0.7$m for $\alpha < \alpha_{c,1}$ we rescale x using $L = 0.28$m. From Fig. 2 it then follows that the bifurcation diagram for y in laboratory space looks as shown in Fig. 3. The parameter L may reflect a body-dimension. In this case, the order parameter equation (1) for y is a body-scaled order parameter equation.

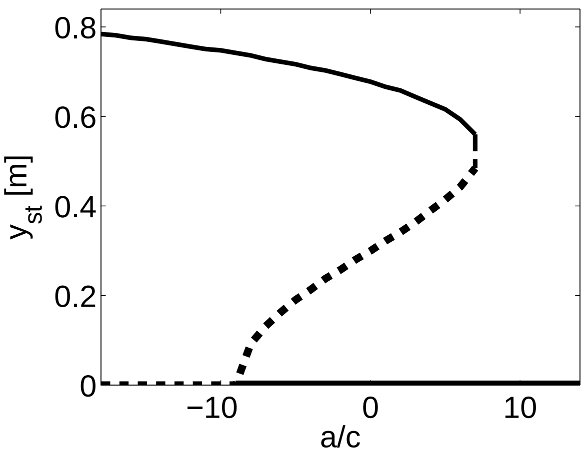

Figure 3. As in Fig. 2 but for the (original) distance order parameter y_{st} measured in the laboratory framework.

3 Discussion

We derived a model for interpersonal distance under the two assumptions that the human spatial behavior is a self-organization process and that the process operates close to bifurcation points. Under these two assumptions, synergetics, a theory of pattern formation and self-organization, applies and predicts the emergence of an order parameter. Conducting a top-down approach, we considered interpersonal distance as the order parameter. This implies that within the proposed framework the interpersonal distance of an actor with respect to another actor is regarded as a time-dependent variable of a dynamical system. The variable converges to a stable fixed point value (stable stationary value) that determines the preferred interpersonal distance of the actor. In a similar vein the Haken-Kelso-Bunz model of bimanual coordination [17], a prism adaptation model [18, 19], and a model for haptic distance perception [20, 21] have been derived in previous studies. In doing so, we advocate that interpersonal distance is a self-organization phenomenon that is governed by principles that hold irrespective of the nature of the underlying neurobiological mechanisms.

In fact, the notion that preferred interpersonal distances correspond to stable fixed points of appropriately defined dynamical systems is consistent with the literature. First of all, individuals are known to exhibit "preferred degrees of closeness" (see Ref. [2], p. 390) or "preferred interaction distances" (see Ref. [2], p. 393). Second, these preferred distances are regarded as equilibrium points at which approach forces and avoidance forces are balanced [2]. While experimental research suggests that on the individual level such preferred interpersonal distances exist, on the population level we need to consider a probabilistic description due to the variability among individuals. That is, we can only predict probability functions that tell us how frequently a given distance will be observed under given circumstances (for a worked out example of an analogous problem in the field of grasping see Ref. [13]).

Interestingly, our derivation required to introduce a scaling parameter L. On the basis of literature data, we determined the value of L to about $L = 0.28$m. This value could correspond to the upper- or lower-arm length of an adult. By introducing a body-scaled parameter and measuring the parameter for an individual, the model (13) can be used to predict the range of personal space distances of that individual.

We considered a transition from the personal distance to the intimate distance as a bifurcation. We assumed that such as change is abrupt rather than continuous and identified the appropriate bifurcation type as a subcritical pitchfork bifurcation. As can be seen from the bifurcation diagram (see Figs. 2 and 3), the bifurcation exhibits hysteresis. Accordingly, when the interaction changes from a personal interaction to a more intimate interaction, that is, when the interaction becomes more intimate, then at a certain critical value the actor adjusts his or her distance to the other person from a personal space distance to an intimate space distance. If subsequently the interaction changes more in the direction of a personal interaction (e.g., due to by chance effects), the actor will not immediately switch back to the personal space distance. Rather, our test person will maintain the intimate space distance because the intimate space fixed point ($y = 0$) is still stable, see Figs. 2 and 3. Consequently, the hysteresis has a stabilizing effect on changes such that behavior is less subjected to the impact of fluctuations. This increased predictability of behavior might be beneficial for establishing social relationships.

While we demonstrated that the case of a subcritical pitchfork bifurcation can be modeled using the parameter $a, c \neq 0$ and $b = 0$, an alternative set of parameters might be of interest as well. For $a, b \neq 0$ and $c = 0$ a numerical analysis similar to the one shown above, reveals a supercritical pitchfork bifurcation. Such a bifurcation may describe transitions that come with a gradual (not jump like) change of the interpersonal distance. For example, during child development it is known that with beginning of the age of 5 the interpersonal distances increases continuously until young adulthood [2]. Therefore, when a change from intimate to personal activities in young children results in a change of the interpersonal differences with respect to an adult, then this may be modeled by means of a control parameter $\gamma = b/a$ that is increased beyond a critical value γ_c. The precise value of $\gamma > \gamma_c$ would depend on age A of a child such that for $A_2 > A_1$ we have $\gamma(A_2) > \gamma(A_1)$.

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