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## **Real-time integration in perceptual updating: The apparent vertical as a case of study**

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Few researchers have occupied themselves with the question as to how visual percepts are updated as a function of time. Using temporal dynamics of the apparent vertical as an example of processes which are slow enough to be conveniently studied, I suggest that updating of spatial frames of reference can be understood in close analogy to serial integration in judgment. For serial integration, two basic modes of processing have been suggested (Anderson, 1981): In the cumulative-averaging mode, information is integrated into a cumulated value for each of the sequentially presented items as soon as it is retrieved from long-term memory, and only this value is kept in short-term memory. Alternatively, in the explicit-storage mode, information is retained piece by piece. Eventually an overall integration is made. Accordingly, one may ask whether the relevant information is completely absorbed in a current percept or is, alternatively, somehow explicitly retained and differentially referred to in stimulus evaluation and resulting perceptual change.

When establishing an analogy to judgment, we must also keep in mind notable differences. Most importantly, while serial integration refers to time in terms of temporal order of items, perceptual updating proceeds in continuous contact with outside reality and, therefore, refers to real time.

### **Paradigm and basic trends**

To draw inferences on updating, we consider time dependencies of two classical illusions, the Aubert phenomenon (AP; Aubert, 1861) and figural induction (FI; Kleint, 1936). We here define by AP and FI deviations of the apparent vertical from physical verticality induced by head tilting and tilted visual frames, respectively. Operationally, these illusions can be determined by adjusting a line to apparent verticality. The experiments to be

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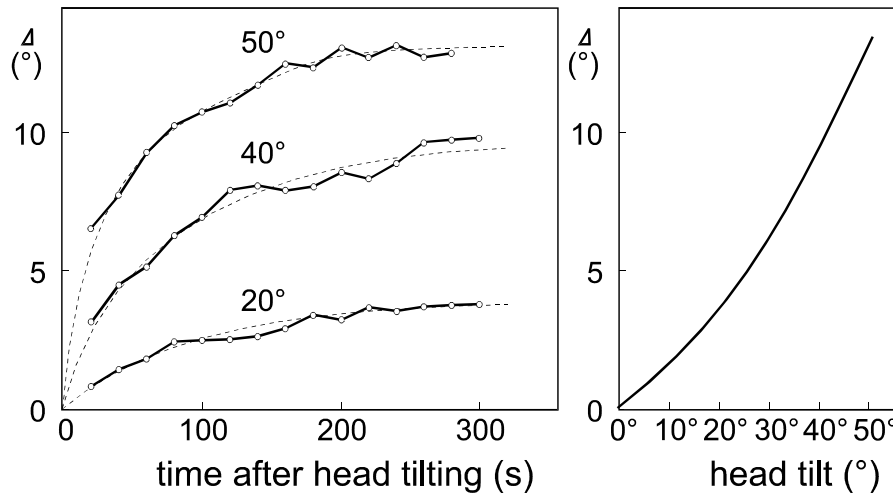


Figure 1. Left: Mean deviations  $\Delta$  (in degrees) of the apparent vertical from physical verticality as a function of time for three degrees of head tilt (“transition functions” of AP). Right: Asymptotes of AP as a function of head tilt (schematic).

reported took place in a darkened room. A luminous line (“test line”) was projected on a semi-transparent pane from behind. Participants were to adjust the line to apparent verticality every 20 sec until their responses became approximately stationary. To investigate FI, a pattern of parallel luminous stripes surrounding the line in a ring was additionally projected. The left-hand panel of Figure 1 shows typical examples of (average) time courses after step-like head inclinations. This family of temporal transition functions can be approximated by

$$Y(\varphi, t) = A(\varphi) \cdot (1 - e^{-t/T}), \quad (1)$$

where  $T$  is a time constant and  $A(\varphi)$  denotes the asymptotic trend of AP as a function of head tilt  $\varphi$  as schematically depicted on the right-hand side of Figure 1.

### Uniform Updating

To arrive at a hypothetical interpretation of the experimental findings in terms of updating, we have to distinguish between “Rate of Change” and

“Rate of Updating”. With reference to Equation 1, Rate of Change can be defined by the time derivation:

$$\dot{Y}(\varphi, t) = A(\varphi) \cdot 1/T e^{-t/T} . \quad (1')$$

Thus defined it is proportional to the asymptotic level of AP and a second part consisting of a constant attenuation and a decay term, both depending on  $1/T$ .

For an appropriate definition of Rate of Updating consider the analogy to judgment. According to Anderson (1981, 1991), the following *cumulative-average* mode of serial integration holds:

$$R_{i+1} = w_i s_i + (1 - w_i) R_i . \quad (2)$$

Here the weight  $w_i$  determines how fast under the impact of inputs given outputs become replaced by new values. It thus defines a measure of the discrete Rate of Updating. In the real-time case, the corresponding recursive rule of *uniform continuous integration* reads:

$$Y(t + dt) = dt/T y(t) + (1 - dt/T) Y(t) , \quad (3)$$

where  $y(t)$  is the input at  $t$ , and  $Y(t)$  and  $Y(t + dt)$  are the outputs at  $t$  and  $t + dt$ , respectively.

Note that the infinitesimal weight  $dt/T$  in Equation 3 is the counterpart of  $w_i$  in Equation 2. Thus  $1/T$  can be defined as *Rate of Updating* underlying the observable changes.

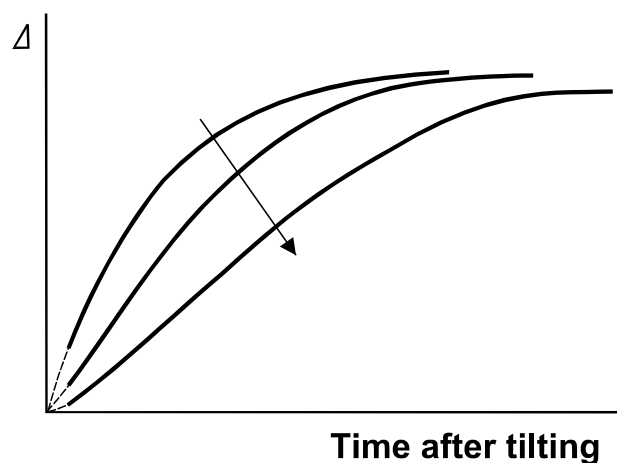
To see that this definition applies to the case at hand, one has to realize (i) that Equation 3 is equivalent to the first-order differential equation

$$\dot{Y} + T \cdot Y = y(t) , \quad (3a)$$

and (ii) that the functions (Equation 1) describing the empirical transitions are solutions to Equation 3a for step inputs of height  $A(\varphi)$  at  $t = 0$ . Consequently, the empirical transition functions of Figure 1 (left) can hypothetically be interpreted as results of *uniform updating after step-like changes in head position*.

### Non-uniform integration

Uniform integration is, however, severely limited in scope, because of second-order modifications of transition functions due to situational factors.



**Figure 2.** Modification of shape of transition functions as a function of number of adjustments to apparent verticality preceding head tilting (schematic).

Such situational dependencies were first reported by Müller (1916). Particularly strong modifications of shape have been found to occur as a function of adjustments of the test line prior to head tilting (Geissler, 1964, 1965). As Figure 2 illustrates, time courses become flatter as the number of adjustments increases. In general, the modified transitions cannot anymore be approximated by negatively accelerated exponential functions like Equation 1. Thus, the question is whether and how the analogy to serial integration in judgment can be expanded so as to include situational modifications of the transition functions.

To capitalize once again on the analogy to judgment, one may compare the modification of the updating regime underlying these observable changes in the shape of the transition functions with the step from cumulative averaging to variable weighting in the explicit-storage mode in serial integration (Anderson, 1991). However, while in serial integration – because of relatively small numbers of serial positions – a largely inductive determination of weights is rendered possible (Anderson, 1991), in perceptual dynamics it is virtually impossible to infer the underlying laws of integration from the continuous changes in the transition functions unless reasonable constraints can be suggested beforehand. As a possible rationale, Geissler (1968) proposed a principle of consistent successive differentiation. It maintains that rules of temporal integration unfold from uniform integration in steps that conform to levels of representational differentiation

of temporal stimulus structures. Considered in this way, uniform integration reflects conditions in which for any possible temporal segmentation none of two adjacent segments are classified as functionally different. The simplest possible differentiation in the representation of stimulus inputs consists in a linear segmentation such that adjacent segments are classified as functionally different. According to the principle, in the integration rule the segments can be differentially weighted against each other. Consistency of successive specification then requires that weighting remains unchanged *within* segments, i.e., uniform.

For a generalization of Equation 1 based on this idea, consider the general solution of Equation 3 wherein the lower border  $-\infty$  is an idealization for the most distant inputs of fading influence:

$$Y(t) = \int_{-\infty}^t e^{-\frac{(t-\vartheta)}{T}} \cdot y(\vartheta) d\vartheta. \quad (4)$$

Equation 4 is a special case of the *convolution integral* for the weighting function  $w(t - \vartheta) = \exp\{-(t - \vartheta)/T\}$ . It can be interpreted to reflect the exponential decay of the impact of  $y(t)$ , conceived as a memory trace. Note that in this sensory-memory interpretation, like in the explicit-storage mode in judgment, it becomes possible to vary weights of traces in retrospect. According to the principle of successive differentiation, segment-wise change of situational conditions should be associated with a segment-wise decomposition of the integral in Equation 4 and a corresponding weighting. To preserve the property of a moving average, the resulting expression must be augmented by a denominator serving continuous re-standardization of weights:

$$Y(t) = \frac{\sum_k W_k \cdot \int_{\Delta_k} e^{-(t-\vartheta)/T} \cdot y(\vartheta) d\vartheta}{\sum_k W_k \cdot \int_{\Delta_k} e^{-(t-\vartheta)/T} d\vartheta}. \quad (5)$$

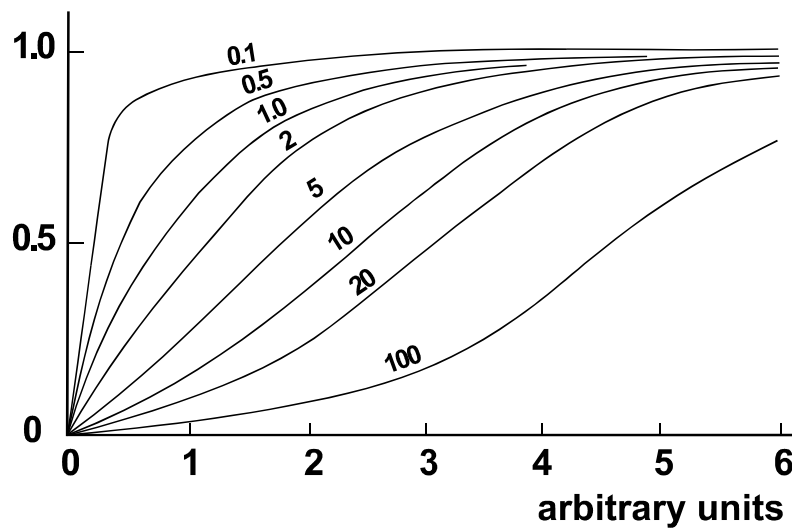
### Applications to AP and FI: The invariance logic

Since the relevant stimulus changes in our experiments (head tilting, presentation and omission of a visual frame) can be approximated by step inputs, Equation 5 is simplified to form an expression with only two free

weights,  $G_1$  and  $G_2$ . For unique description of temporal characteristics it even suffices to consider system responses to unit inputs (i.e.,  $y = 0$  for  $-\infty \leq \vartheta \leq 0$ , and  $y = 1$  for  $0 \leq \vartheta \leq t$ ). Then Equation 5 turns into a family of functions of the logistic type:

$$Y_U(t) = \frac{W_2 \cdot (1 - e^{-t/T})}{W_1 \cdot e^{-t/T} + W_2 \cdot (1 - e^{-t/T})} = \frac{1 - e^{-t/T}}{g \cdot e^{-t/T} + 1 - e^{-t/T}}. \quad (6)$$

Figure 3 illustrates the predicted time courses for  $g = W_1/W_2$  in a range from 0.1 to 100. Unlike Figure 2 this picture shows for  $g < 1$  courses steeper than the exponential trend and for  $g > 2$  flat s-shaped functions.



**Figure 3.** Predicted transition functions  $Y(t)$  for the standard interval  $0 \leq Y < 1$ . The parameter is the relative weight  $g = G_1/G_2$ . Note the steep courses for  $g < 1$  and s-shaped functions for  $g > 2$ .

When applying Equation 6 to experimental data, it is important to note that “consistent successive differentiation” is not merely a tool for formal specification, but involves substantive implications. Most importantly, it entails that  $T$  as a descriptor of the base-level dynamics of uniform integration captures a property of the processing system that thus may vary between

individuals, but should be constant under stimulus-related changes. In the same way,  $T$  may differ for different classes of output constituents, but for a given output entity – in the case at hand the apparent vertical – it should not depend on the specific external sources of information. Accordingly, I hypothesize that approximate invariance holds (i) under variation of shape of transition function and (ii) across postural (AP) and visual (FI) effects.

### Experiment 1: Invariance under change of function shape

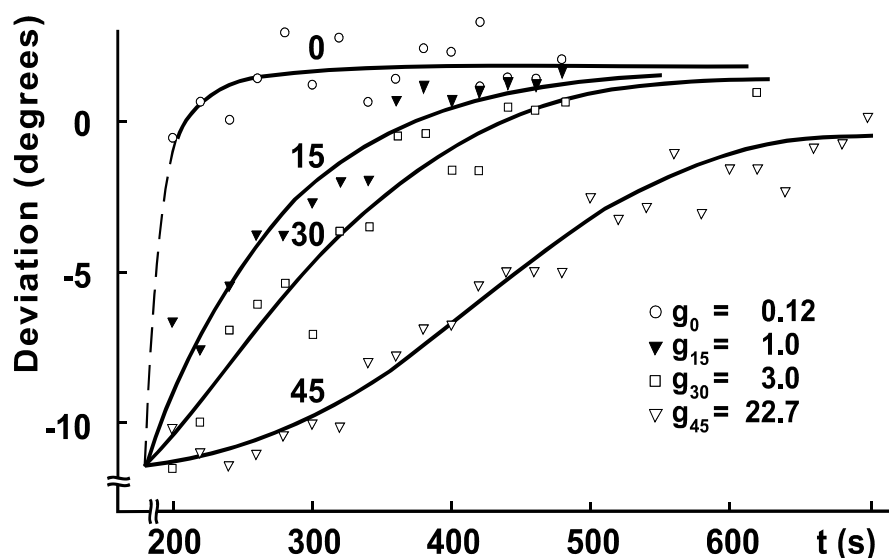
An experiment designed to test invariance of  $T$  under change of shape of transition functions induced by situational conditions was carried out with three participants. During a fore-period with upright head, number of adjustments was varied between  $N = 0$  and  $N = 45$ .

Figure 4 depicts for one participant averages of four replications and the best fits of Equation 6 to the data. To enable a reasonable computation for  $N = 0$ , the best-fitting function was forced to agree at  $t_0 = 180$  sec with the extrapolation from the flattest curve. Note that the predicted alteration from a near step-like change to s-shaped functions is qualitatively well portrayed. Table 1 summarizes the parameter estimates. While  $T$  varies unsystematically exhibiting deviations from the means between 10 and 17%, the systematic changes of  $g$  associated with  $N$  are dramatic.

Interestingly,  $g$  varies approximately as a logarithmic function of fore-period duration.

Participant		$N$			
		0	15	30	45
1	$T[s]$	50.6	94.1	86.3	78.4
	$g$	0.1	1.1	3.0	22.7
2	$T[s]$	-	37.7	-	47.5
	$g$	-	3.0	-	125
3	$T[s]$	-	87.6	-	72.4
	$g$	-	2.4	-	13.7

**Table 1.**  $T$  and  $g$  as functions of the number  $N$  of adjustments before head tilting.



**Figure 4.** Time courses of AP after  $N = 0, 15, 30, 45$  adjustments preceding head tilting; best fits according to Equation 6 obtained by non-linear regression.

### Experiments 2 and 3: Invariance across AP and FI

In two experiments with a total of eight participants, the hypothesis was tested that  $T$  is invariant across AP and FI. In Experiment 2, when AP after the head tilting had reached an approximately stationary level, FI was elicited by frames tilted relative to this level. In Experiment 3, the sequence of conditions was reversed. Figures 5a and 5b show the respective time courses for one participant averaged from six replications for each FI condition.

Due to slight asymmetries, minor deviations from physical verticality appeared also during the foreperiod. For two participants there were sufficient data to estimate  $T$  and  $g$  for this condition. Thus, from Experiment 1 altogether ten pairs of estimates were obtained for AP and eight for FI. Experiment 2 yielded two additional pairs of estimates. In Figure 6, the values obtained for FI ( $T_{FI}$ ) are plotted against those for AP ( $T_{AP}$ ). Note that in six out of the 12 cases the data come very close to the ideal straight line of slope 1. In four further cases, agreement is acceptable. Clear exceptions are the results for participants  $S7$  and  $S8$ . Yet, in both these cases the final adjustments



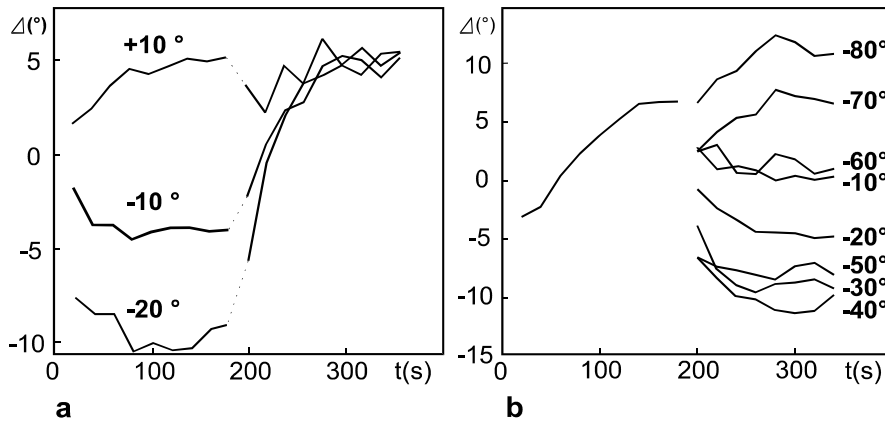


Figure 5. Explanation in the text.

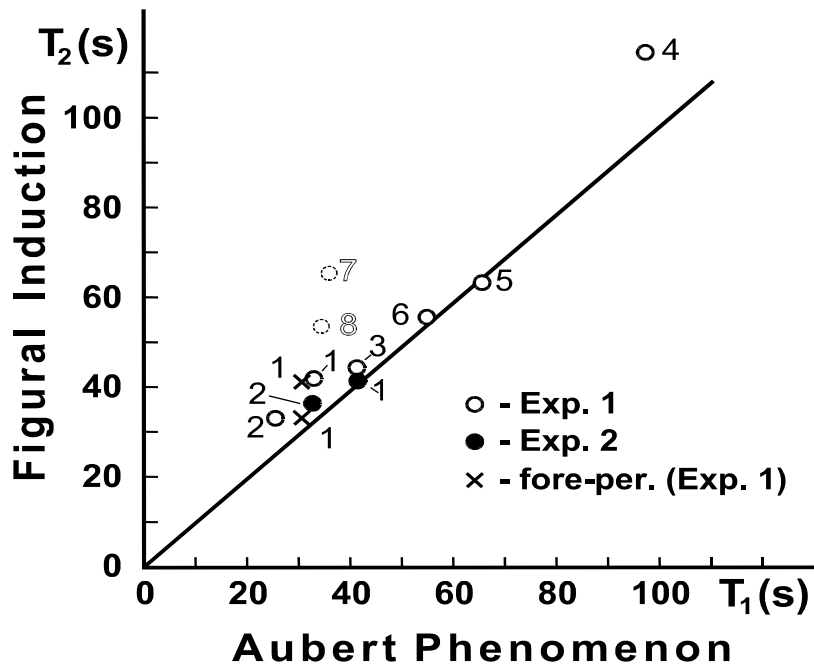


Figure 6. Estimates of  $T$  for FI ( $= T_2$ ) for eight participants plotted against those for AP ( $= T_1$ ). See inset legend and text.

for FI did not come sufficiently close to stationarity, which led to unreasonably high estimates of asymptote values. Omitting these discrepant figures, regression yields a slope of 1.10 ( $r = 0.97$ ). A small intercept of 1.64 ms ( $\approx 1.5\%$  of the range) suggests that there is no major second determinant involved. Note that between individuals,  $T$  varies in a range from  $\sim 30$  sec to  $\sim 100$  sec. By contrast, in the two examples of three estimates for the same individuals (Participants 1 and 2) these lie in a small area even though they are representative of quite different conditions (see inset legend of Figure 6).

## Discussion

### *Special conclusions*

The evidence from the three experiments suggests that  $T$  corresponds to a stable characteristic of individuals. A lack of systematic variation of  $T$  under extreme variation of shape of transition functions indicates (as a hitherto unknown functional relationship) that updating after head tilting is accelerated or slowed down depending on  $g$ , a parameter that can be interpreted as a measure of reliability of information on the apparent vertical prior to change relative to that after change. Approximate invariance across postural and visual induction (AP and FI) indicates that  $T$  signifies a dynamic property of central updating.

What is demonstrated relates to one of the fundamental orientation systems in vision. The corresponding processes of real-time updating are particularly slow. Judged by the values of  $T$ , they are located at the upper end of a cascade of memory-like processes of increasing temporal extension that are involved in perception (see e.g. Ischikawa, 1982). It would appear tempting to apply a similar analysis to faster modular components.

### *Relations to Functional Measurement*

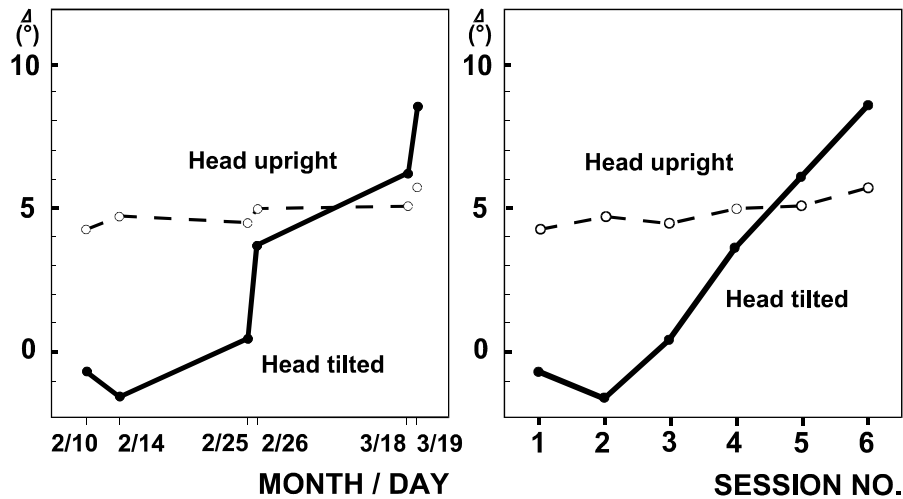
The results support the idea that temporal short-term dynamics of the apparent vertical can be understood in close analogy to serial integration in judgment (cf. Anderson & Hubert, 1963). Likewise, there are deep analogies in the applied logics of analysis. As it holds for a mental algebra identified by a fan pattern, convolution – of which Equation 4 is a special case – can formally be represented as a product  $y(t) * w(t)$ . In analogy to functional measurement,  $w(t)$  can be recovered by de-convolution from integrative responses,  $Y(t)$ , for example to step inputs. However, unlike known mental algebra, the operation “\*” denotes an integral of infinitely many

products of numbers. Relationships are even more complex in the case of non-linear expansions like Equation 5. Still, in the same way as outcomes of functional measurement enable further substantive investigations, the invariance of  $T$  provides a basis for further inquiry because of simultaneous validation of the rule (Equation 6) of situational weighting. For example, situational stabilization of frames of reference or inter-modal integration of postural and visual information can be examined.

*Contrast to peripherally oriented physiological views*

While the above analysis does not depend on specific physiological assumptions, the resulting picture is not neutral against principal alternative conceptions on neural processing architectures. A view dominating the entire history of research maintains that percepts are the final outcomes of a series of transformations applied to sensory inputs. In this perspective, the autonomous (i.e., not stimulus-related) temporal dynamics of perception is expected to echo primarily modality-specific peculiarities of peripheral processing and transmission of sensory information. By contrast, approximate invariance of  $T$  across AP and FI suggests that modality-specific time dependencies of visual versus postural contributions should be negligible in comparison with a unique central contribution.

Updating, considered as a programmatic concept for understanding the short- and long-term evolution of percepts, indeed necessitates a complete rethinking of the classical doctrine. This becomes more obvious when taking into consideration not only dynamic characteristics but also the absolute sizes of AP and FI. In the peripherally oriented view, the stationary degrees of the illusions have been attributed to the peculiar transducer characteristics of the receptors involved and to limitations of subsequent neural calibration (Schöne, 1959; Bischof, 1966, 1995). By contrast, in a perspective focusing on central processing, absolute localization of the apparent vertical is to be conceived as resulting from optimization of percept-internal relations of which feedback information on physical verticality is a common but not universally mandatory part (cf. also Geissler, 1991). This view is corroborated by results obtained when no feedback was provided, which indicate a free floating of the apparent vertical – in contradiction to any monotonous relation to head position. As an example relating to our experiments, Figure 7 shows mean deviations from physical verticality increasing over weeks. The plot against session number (right panel) demonstrates stable “learning” effects of practically no decay revealing a cross-over of the trend for 40° head inclination with that for upright head position.



**Figure 7.** Mean AP for one participant as a function of date of series (left) and of session number (right). Note the near-linear increase after the first session.

Clearly, these results are at variance with any approach assuming a straightforward transformational relation between stimuli and perceptual effects. They are, however, in harmony with conceptions that attribute to percepts an active role in the process of perception (e.g. McKay, 1963), and with more recent claims that attribute to stimulus patterns the role of instructions to infer the proper constraints for central processing (cf. Freeman, 1990).

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### Abstract

Delayed changes in the position of the apparent vertical after step-like changes of stimulus conditions are used to explore perceptual updating. It is shown that the processes of temporal integration involved can be conceived as real-time analogues of serial integration in judgment. Invariance of the overall rate  $1/T$  of updating provides a basis to argue (i) that perceptual change is accelerated or slowed down as a function of relative weighting of adjacent situations and (ii) that metric characteristics of temporal change are unique to the integrative outcome rather than specific to modal contributions of postural versus visual information. The results suggest rejection of accounts in terms of modality-specific transmission of sensory information in favor of a memory-based central explanation of temporal integration.

### **Riassunto**

Cambiamenti ritardati della posizione della verticale apparente in seguito a cambiamenti discreti delle condizioni stimolo vengono usati per indagare processi di aggiornamento percettivo. Viene mostrato che i processi di integrazione temporale implicati possono essere concepiti come analoghi in tempo reale delle integrazioni seriali nel giudizio. L'invarianza del tasso di aggiornamento complessivo  $1/T$  fornisce la base per argomentare (1) che il cambiamento percettivo è accelerato o decelerato in funzione del peso relativo di situazioni adiacenti e (2) che le caratteristiche metriche del cambiamento temporale sono uniche del risultato integrativo piuttosto che specifiche dei contributi modali della informazione posturale o di quella visiva. I risultati suggeriscono il rifiuto di interpretazioni in termini di trasmissione delle informazioni sensoriali specifica delle modalità e sono in favore di una spiegazione centrale della integrazione temporale basata sulla memoria.

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