Evidence for Transitional Coding of Human Motor Representations

Moritz Schaaf[1], Solveig Tonn[1], Katharina A. Schwarz[1, 2, 3], Wilfried Kunde[4], and Roland Pfister[1, 2]
[1] Department of Psychology, Trier University
[2] Institute for Cognitive and Affective Neuroscience, Trier University
[3] Department of Behavioural and Cognitive Sciences, University of Luxembourg
[4] Department of Psychology, Julius Maximilians University of Würzburg

How are body movements represented? While research suggests that movements are selected and initiated by anticipating their perceptual effects, the representational content of these anticipated effects remains underspecified. Specifically, it is unknown whether effect anticipations represent desired perceptual end states or intended perceptual changes leading to these end states. Here, we introduced a novel method to distinguish between the two representational contents and applied it in three preregistered experiments. Our results consistently favored transitional codes, indicating that the mind represents and controls body movements through the perceptual changes that they reliably produce.

Public Significance Statement

How does the human mind control body movements? While there is evidence that we move by mentally anticipating what we will see or feel when we move, it is unclear whether such action representations rely on the final result of the movement or on the changes leading to that result. The present study found that we guide our body movements by anticipating how our perception will change as we move. This finding also helps us understand how and when we feel in control of our actions and how action representations shape later perception.

Keywords: motor control, ideomotor effect anticipations, representational format, efficient coding

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Human cognition is optimized for controlling goal-directed body movements, the sole means by which agents can shape their environment (Dennett, 1991; Prinz et al., 2013). Although actions like pointing, walking, or grasping appear effortless, the underlying physiological and cognitive "machinery" is extraordinarily complex and delicate. This complexity becomes particularly evident in the field of robotics, where even modern robots fail to replicate the fluidity and efficiency of human motor control (Della Santina et al., 2023; Rus & Tolley, 2015). Similarly, while computational neuroscience has developed highly sophisticated models of motor

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Moritz Schaaf https://orcid.org/0000-0002-9959-2928

The authors report all data exclusions, manipulations, and measures in the study. All experiments were preregistered prior to data collection. The exploratory analysis in the supplemental material is clearly marked as exploratory. For all experiments, materials, raw data, analysis scripts, and preregistrations (including design, hypotheses, and analysis plan) are publicly available at https://osf.io/p5n6u. Data were collected in 2022 and 2023. The data and ideas presented in this article were shared at the 23rd Conference of the European Society for Cognitive Psychology (Porto, Portugal) on September 9, 2023; the 66th Tagung experimentell arbeitender Psycholog*innen (Regensburg, Germany) on March 18, 2024; and the 65th Annual Meeting of the Psychonomic Society (Psychonomics; New York, United States) on November 23, 2024. This work received approval from the local ethics board (GZ 2019-27). The authors have no conflicts of interest to disclose. This work was funded by the German Research Foundation Grants PF 853/10-1 and PF 853/11-1 awarded to Roland Pfister and Grant SCHW 1955/1-2 awarded to Katharina A. Schwarz.

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Correspondence concerning this article should be addressed to Moritz Schaaf, Department of Psychology, Trier University, Johanniterufer 15, 54290 Trier, Germany. Email: moritz.schaaf@uni-trier.de

control (Heald et al., 2021; Wolpert et al., 2011), the representational format of the cognitive processes enabling such actions remains unclear (Custers, 2023).

How, then, do humans represent and control their movements? The *ideomotor principle* is a classic answer to this philosophical question (Herbart, 1825; James, 1890; see also Hommel et al., 2001; Prinz, 1992): Motor patterns and their perceptual effects become associated through experience. Crucially, these associations are assumed to be bidirectional, implying that (a) activating a certain motor pattern will re-activate codes of its corresponding perceptual effects, and (b) anticipating a certain perceptual effect will re-activate its corresponding motor pattern. Extensive evidence supports these core principles of ideomotor action control (for a review, see Shin et al., 2010), demonstrating that action–effect anticipation is pivotal for action control. However, most corresponding studies did not specify what is being anticipated, thereby neglecting the fundamental question of how effects—and, by extension, actions—are represented within these action–effect associations (Pfister, 2019).

Specifically, modern ideomotor theorizing often emphasizes that actions are represented in terms of desired end states (e.g., Greenwald, 1970; Janczyk et al., 2017; Shin et al., 2010). To cite an example: "touching a light switch and turning on the light would create an association between the representation of the light *being on* [emphasis added] and the motor pattern of touching the switch" (Watson et al., 2015, p. 45). We will refer to this hypothetical cognitive architecture as *goal-based* coding, with "goal" denoting a desired perceptual state after motor activity (Hommel, 2022).

Some classic ideomotor theorizing, by contrast, consistently uses the term "changes" to denote the perceptual effects that become associated with motor activity (e.g., Herbart, 1825, German term: *Veränderungen*). This alternative cognitive architecture thus proposes that the *transition* from the current state to the desired end state serves as the defining feature of action representations. For example, touching a light switch would become associated with the corresponding perceptual change, an increase in brightness, not to the perceptual state of the light being on. Crucially, both transitional as well as the goal-based coding can explain the available empirical findings, rendering this central aspect of ideomotor action control underspecified.

Tentative evidence in favor of transitional coding comes from the observation that different start states can require different actions to achieve the same end state (Janczyk et al., 2012; Kunde et al., 2017). However, experimentally varying start states and transitions while keeping the end state constant cannot provide conclusive evidence for either goal-based or the transitional coding. Any result from such studies can be interpreted as either showing transitional representations or as showing contextualized end state representations (Kunde et al., 2017). To isolate and directly compare the relative contributions of perceptual end states and perceptual transitions, the start state should therefore be neutral while transitions and end states are both manipulated. Here, we implemented this strategy in three preregistered experiments.

Experiment 1

To investigate the anticipation of future perceptual effects, the current experiments manipulated the spatial compatibility between responses and subsequent visual effects. If action control relies on representations of response–contingent effects, then anticipating (future) effects should facilitate actions that are compatible with their anticipated effects, a pattern that has indeed been consistently observed (response–effect compatibility; Kunde, 2001; see Janczyk et al., 2023, for a recent multilab replication).

To distinguish between transitional and goal-based representations, we employed two different effect types: In the onset condition, leftward or rightward mouse movements produced visual stimulation on the left or right side of the screen by dynamically making a gray rectangle appear. In the offset condition, in contrast, these movements removed existing visual stimulation from the left or right side of the screen by dynamically making parts of an already displayed rectangle disappear. As a result, both onset and offset effects consisted of lateralized transitions that resulted in lateralized end states, with end state referring to the presence of remaining stimulation rather than to the absence of removed stimulation. Because we further manipulated the spatial relation between responses and effects, spatially compatible or incompatible transitions resulted in spatially compatible or incompatible end states in a full crossover design (see Figure 1).

The onset condition mirrors previous work in the response–effect compatibility paradigm as the spatial features of the transitions correspond to the spatial features of the end states, confounding both types of compatibility. For example, a rightward movement may produce a right rectangle (rightward, compatible transition), yielding a right rectangle as (compatible) end state. In the crucial offset condition, however, the spatial features of the transitions diametrically oppose the spatial features of the end states, pitting both types of compatibility directly against each other: Compatible offset transitions result in incompatible end states, and incompatible offset transitions result in compatible end states. For example, a rightward movement may remove a left rectangle (leftward, incompatible transition), yielding a right rectangle as (compatible) end state. Consequently, comparing onset effects (which yield similar predictions for transition-based and goal-based representations) with offset effects (which yield diametrically opposed predictions for transition-based and goal-based representations) is diagnostic for the relative contributions of transitions and end states.

Method

Transparency and Openness

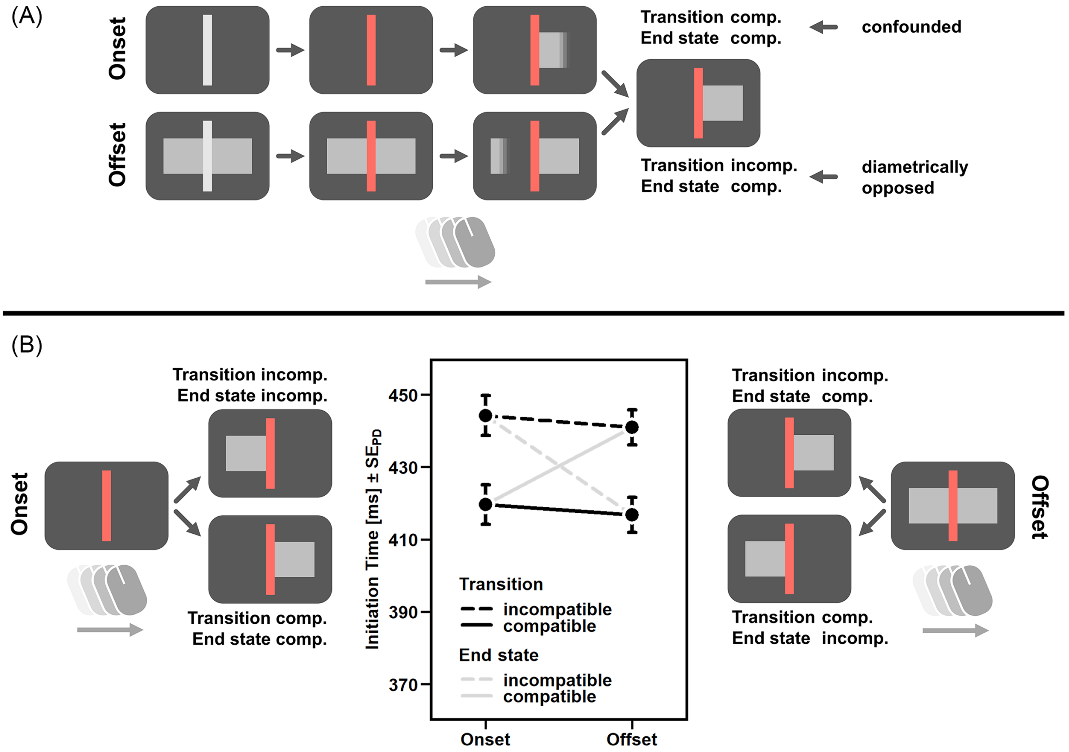
We report all data exclusions, manipulations, and measures in the study. For all experiments, materials, raw data, analysis scripts, and preregistrations (including design, hypotheses, and analysis plan) are publicly available at https://osf.io/p5n6u.

Participants

Eighty participants ($M_{\text{age}} = 23.8$ years, $SD = 7.1$) were recruited online, provided written informed consent, and received monetary compensation or partial course credit. Participants self-identified their gender by selecting one of three options: female ($n = 61$), male ($n = 19$), or gender-diverse ($n = 0$). At an α of .05, this sample size provides a power of >.95 to observe response–effect compatibility effects as previously observed for initiation times of mouse movements (all prior $d_z \geq 0.45$; see Tonn et al., 2025, for an overview) and allows for counterbalancing.

Figure 1

Design and Results of Experiment 1



Note. Panel A: Participants responded to the color of a vertical bar by moving the mouse to the left or right. These mouse movements resulted in end states (gray rectangles) that could be either spatially compatible (comp.) or incompatible (incomp.) with the action. In the onset condition, actions dynamically produced novel stimulation, while in the offset condition, they dynamically removed existing stimulation. As a result, the compatibility of transitions aligned with the compatibility of end states in the onset condition. In the offset condition, however, the compatibility of transitions diametrically opposed the compatibility of end states. Onset as well as offset effects started at the screen center and moved outwards (exemplary screen recordings are available at https://osf.io/p5n6u). Panel B: Initiation times followed the predictions of transitional representations rather than those of goal-based representations. Error bars denote the SE_{PD}, computed separately for the onset and offset condition (Pfister & Janczyk, 2013). SE_{PD} = standard error of paired differences. See the online article for the color version of this figure.

Stimuli and Procedure

Before each trial, a light gray oval (2.4% × 3.3% of screen width × height) was rendered either directly against the black background (onset condition) or against a dark gray rectangle (80% × 65%; offset condition). This oval prompted participants to reset their mouse cursor to the center of the screen. The actual trial started 500 ms after reaching this neutral position. This was signaled by the disappearance of the oval and mouse cursor, along with the appearance of a light gray bar (2.4% × 100%) dividing the screen into a left and right half. This vertical bar changed color after 750 ms, serving as stimulus (red vs. blue) signaling the required response (leftward vs. rightward mouse movement). As visual effect, the mouse movements dynamically produced (onset condition) or removed (offset condition) parts of a gray rectangle until an (invisible) end area (10% × 100%) on the left and right side was reached. These dynamic transitions started at the screen center and could either align with the response direction (compatible transition) or oppose it (incompatible transition). Consequently, both onset and offset transitions resulted in the same end states: a gray rectangle (40% × 65%) on either the left or right side of the screen. In correct trials, the end state was displayed for 750 ms before the next trial started. Otherwise, appropriate feedback was displayed for 2,000 ms.

Participants completed 12 blocks of 40 trials each. The stimulus–response mapping remained constant within participants but was counterbalanced between participants. Effect type (onset vs. offset) and response–transition compatibility (compatible vs. incompatible) were manipulated within participants, between blocks (three consecutive blocks per condition). Effect type was counterbalanced between the first and second halves of the experiment, and response–transition compatibility was counterbalanced within each effect type.

Results

For our analyses, we coded each condition as coming with either compatible or incompatible transitions. In the onset condition (baseline), transitional coding and goal-based coding both predict better performance with compatible transitions (and compatible end states) than with incompatible transitions (and incompatible end states). For the critical offset condition, transitional coding predicts the same influence on performance as for the onset condition, that is, better performance with compatible transitions (but incompatible end states) than with incompatible transitions (but compatible end states), whereas goal-based coding predicts a reversed influence.

We analyzed initiation times (ITs), movement times (MTs), and error percentages (PEs; see Table 1 for descriptive statistics). IT was measured as the time from the onset of the imperative stimulus until the invisible cursor left the vertical bar. MT was measured from this point in time until the cursor reached the end area. For IT and MT analyses, trials with errors (5.8%) and trials following errors were excluded. Trials were removed as outliers if ITs deviated more than 2.5 *SD*s from the participants' corresponding cell mean (2.3%). The final sample for IT and MT analyses consisted of 87.0% of the original trials. Data were analyzed using 2 × 2 analyses of variance with response–transition compatibility (compatible vs. incompatible) and effect type (onset vs. offset) as within-subjects factors.

ITs

Figure 1B shows ITs for all experimental conditions. Responses were initiated faster with response–compatible transitions than with response–incompatible transitions (418 ms vs. 443 ms), $F(1, 79) = 31.55$, $p < .001$, $\eta_p^2 = .29$. All other *F*s < 1. The response–transition compatibility effect was thus equally present for onset effects ($\Delta = 25$ ms), $t(79) = 4.47$, $p < .001$, $d_z = 0.50$, and for offset effects alike ($\Delta = 24$ ms), $t(79) = 5.00$, $p < .001$, $d_z = 0.56$.

MTs

Responses with onset effects were executed faster than responses with offset effects (100 ms vs. 109 ms), $F(1, 79) = 3.98$, $p = .049$, $\eta_p^2 = .05$. All other *F*s < 1.

PEs

Fewer errors were made with response–compatible transitions than with response–incompatible transitions (5.1% vs. 6.5%), $F(1, 79) = 12.89$, $p = .001$, $\eta_p^2 = .14$. Accuracy was not significantly influenced by effect type, $F < 1$. Response–transition compatibility and effect type interacted, $F(1, 79) = 5.58$, $p = .021$, $\eta_p^2 = .07$, with a smaller response–transition compatibility effect with onset effects ($\Delta = 0.6\%$), $t(79) = 1.55$, $p = .126$, $d_z = 0.17$, than with offset effects ($\Delta = 2.2\%$), $t(79) = 3.63$, $p < .001$, $d_z = 0.41$.

Discussion

The data of the onset condition replicated the usual response–effect compatibility effect: Responses were initiated faster and more accurately when the subsequent effects were spatially compatible rather than incompatible with the movement. Crucially, the data of the offset condition revealed that this influence was driven by transitions rather than end states: Responses were initiated faster and more accurately when transitions were compatible (and end states incompatible) than when transitions were incompatible (and end states compatible). Thus, the data from Experiment 1 provide strong support for transitional representations.

While initiation times were not modulated by the compatibility of end states, the interaction observed in the error rates could, at first glance, be interpreted as tentative support for goal-based representations. However, such mixed representations would predict a larger influence of response–effect compatibility in the onset condition (where transitions and end states align) than in the offset condition (where they contrast). Yet, the opposite pattern was observed, indicating that this interaction reflects either a different process or a false positive.

Similarly, neither transitional nor goal-based representations predict movement time differences between onset and offset effects. This main effect may reflect a false positive or increased monitoring demands from the lower saliency of offset effects (see Miller, 1989; Schaaf et al., 2022b; Wirth et al., 2018).

Experiments 2 and 3

Because Experiment 1 used forced-choice actions, the correct response was entirely determined by the imperative stimulus. This creates contingencies not only between responses and effects but also between stimuli and effects. Therefore, the observed influence of anticipated perceptual transitions could potentially result from exogenous activation spreading via stimulus–effect associations rather than from endogenous activation during action planning (Kunde, 2001; see also Janczyk, 2023; Schaaf et al., 2022a; Schonard et al., 2021; Vogel-Blaschka et al., 2024). To disentangle these mechanisms, a third stimulus signaled free-choice actions in Experiments 2 and 3 (reported in detail in the Supplemental Material). Both experiments replicated the response–transition compatibility effect for forced-choice and free-choice actions alike (see Table 1). Thus, stimulus–effect associations were not the primary cause of the observed data pattern, reinforcing the

Table 1

Descriptive Statistics for All Experiments and Experimental Conditions

		IT (ms)			MT (ms)			PE (%)		
Exp.	Condition	Comp.	Incomp.	$\Delta \pm SE_{PD}$	Comp.	Incomp.	$\Delta \pm SE_{PD}$	Comp.	Incomp.	$\Delta \pm SE_{PD}$
1	Onset effects	420	444	25 ± 5	100	101	1 ± 5	5.4	6.1	0.6 ± 0.4
	Offset effects	417	441	24 ± 5	108	111	3 ± 6	4.8	7.0	2.2 ± 0.6
2	Free-choice	512	538	27 ± 8	101	99	−2 ± 6			
	Forced-choice	471	513	42 ± 9	87	98	11 ± 9	5.7	8.3	2.5 ± 0.9
3	Free-choice	502	525	23 ± 6	94	100	6 ± 5			
	Forced-choice	464	505	41 ± 8	91	93	3 ± 4	3.4	4.4	1.0 ± 0.4

Note. Exp. = experiment; IT = initiation time; MT = movement time; PE = percentage errors; comp. = response and transition compatible; incomp. = response and transition incompatible; Δ = incompatible–compatible; SE_{PD} = standard error of paired differences, computed separately for each Δ (Pfister & Janczyk, 2013). Experiment 1 used only forced-choice actions and manipulated effect type (onset vs. offset), whereas Experiments 2–3 used only offset effects and manipulated action type (free-choice vs. forced-choice).

conclusion that movements are represented by the perceptual changes they consistently produce.

General Discussion

How are body movements cognitively represented? The ideomotor principle suggests that actions are coded in terms of the perceptual effects they produce, but current formulations of this classical theoretical approach remain underspecified regarding the content of these effect representations. Here, we addressed a central theoretical distinction and investigated whether perceptual effects are represented as static end states (“terminal goal states”; Janczyk et al., 2017, p. 471; see also Greenwald, 1970) or as changes (Kunde et al., 2017; see also Herbart, 1825). Our results provide an unequivocal answer. Across three preregistered experiments, our data consistently favored transitional coding over goal-based coding. Specifically, actions were strongly influenced by their compatibility with anticipated changes, and anticipated end states exerted little to no influence. This suggests that movements are encoded through the perceptual transitions they produce. Below, we outline several possible arguments highlighting the theoretical advantages of transitional coding.

For one, a change-based format naturally provides sparse encoding and thus efficient storage of information (e.g., Salomon, 2007). Instead of associating movements with all co-*occurring* perceptions, transitional codes selectively capture only co-*varying* perceptions. Put differently, transitional codes reduce redundancy by exploiting regularities within perceptual information and by filtering out features with no variance or high autocorrelation—these features have not changed and conceivably provide no meaningful information about the specific consequences of an action. Thus, transitional representations elegantly accommodate practical considerations about efficient coding in neural systems, as a reduction in the amount of represented information optimizes metabolic cost and processing speed (Barlow, 1961; Olshausen & Field, 2004). Both computational and ideomotor-inspired models of motor control propose that the perceptual consequences of a movement are predicted or anticipated during or before the movement. If these anticipations were generated as complete states, irrelevant details of the environment would need to be activated, thereby violating the principle of efficient coding. Therefore, it is not surprising that both theoretical frameworks explicitly acknowledge that representations are trimmed to include only relevant information (e.g., Frith et al., 2000, p. 1772; Memelink & Hommel, 2013). Transitional coding offers a straightforward and mechanistic explanation of how representations remain focused on these relevant features.

Furthermore, transitional coding addresses a crucial theoretical challenge of the ideomotor principle: the “circular reflex” problem (Greenwald, 1970; Kunde et al., 2017). This problem describes a self-sustaining activation loop which arises from the core idea of ideomotor approaches that perceptual codes can activate motor codes. That is, if a movement eventually generates the effects that were anticipated to control this movement in the first place, the effects will exogenously activate the corresponding perceptual codes, thereby continuously re-activating the motor pattern. While a qualitative distinction between perceiving and anticipating can solve this problem (Greenwald, 1970; but see James, 1890), transitional coding significantly limits the practical implications of circular reflexes without such auxiliary assumptions. Unlike state-based representations, transition-based representations are inherently short-lived—they are activated only transiently during moments of perceptual change and dissipate as the change subsides. In addition, the mechanism of sensory attenuation actively counteracts these short-lived activations, as perceptual changes caused by one’s own actions are automatically dampened by the brain (Weiskrantz et al., 1971, see also Horváth, 2015). Thus, the transient nature of change-based coding avoids continuous circular activation, and sensory attenuation minimizes any residual risks of transient circular activation. Conversely, if perceptual phenomena like sensory attenuation rely on codes of anticipated action effects (Dogge et al., 2019), the present findings would suggest that motor-induced perceptual biases affect transitions between perceptual states rather than the states themselves. This perspective also extends to ideomotor-inspired accounts of the sense of agency, which propose that feelings of agency arise from a match between anticipated and actual perceptual effects (Schreiner et al., 2025).

Finally, transitional representations align with classic findings on adaptation level effects, which demonstrate that perception and judgments are highly sensitive to stimulus changes (e.g., Helson, 1948). This is particularly evident in proprioception, where specialized neurons (group la afferents) encode the rate of muscle length change (e.g., Matthews, 1964; Tuthill & Azim, 2018). Therefore, action representations might incorporate such information, as proprioceptive consequences of actions can be crucial for ideomotor effect representations (Pfister, 2019). However, sensitivity to change also extends beyond basic perceptual properties. Findings from behavioral economics, for instance, indicate that individuals are more sensitive to changes of utility (e.g., monetary gains and losses) than to absolute states of utility (Kahneman & Tversky, 1979). Similarly, contemporary motivational theories also emphasize the significance of perceptual changes for action selection (e.g., Eder, 2023). It thus appears as if change-based representations are integral for human cognition, with the present experiments highlighting their pivotal role even for low-level sensorimotor action control.

Constraints on Generality

Because the ideomotor principle is thought to be universal (e.g., Herbart, 1825; Pfister, 2019), we collected a convenience sample of young adults without neurological injury or disease. Nonetheless, the results might not generalize to different populations across the lifespan or individuals with neurological injury or disease.

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