Motor Habituation: Theory and Experiment

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***Abstract*—Habituation is the phenomenon that responses to a stimulus weaken over repetitions. Because habituation is selective to the stimulus, it can be used to assess infant perception and cognition. Novelty preference is observed as dishabituation to stimuli that are sufficiently different from the stimulus to which an infant was first habituated. In many cases, there is also evidence for familiarity preference observed early during habituation. In motor development, perseveration, selecting a previously experienced movement over a novel one, is commonly observed. Perseveration may be thought of as analogous to familiarity preference. Is there also habituation to movement and does it induce novelty preference, observed as motor dishabituation? We apply the experimental paradigm of habituation to a motor task and provide experimental evidence for motor habituation, dishabituation and Spencer-Thompson dishabituation. We account for this data in a neural dynamic model that unifies previous neural dynamic accounts for habituation and perseveration.**

***Index Terms*—Habituation, Exploration, Learning, Movement Generation, Neural Model, Dynamic Field Theory**

I. INTRODUCTION

Habituation is perhaps the most basic form of learning observed across many species and behaviors [1]. In habituation, the response to a stimulus weakens across repetitions. Habituation is readily observable in infants and is a primary tool of studying infant perception and cognition [2]. In infant habituation, a visual or auditory stimulus is presented to the infant and a reaction to the stimulus is recorded, often as an orientation response (e.g. duration of looks at the presented stimulus) or as a physiological response (e.g. heart rate as a measure of arousal). Across repetitions of such stimulus presentations, responses tend to diminish, leading to characteristic habituation profiles.

Habituation is selective: When a new stimulus is presented, a stronger response may be reinstated, a phenomenon referred to as dishabituation. By measuring how much stimulus change is needed to induce dishabituation, researchers make inferences about discrimination. Habituation has been used, therefore, as a method to study infant perception [3]. Conversely, the absence of dishabituation to a varied stimulus may be interpreted as an index of the recognition of the new stimulus as being in the same category as the stimulus to which the infant was habituated. This perspective on habituation can be used to study infant cognition [4]. To seek evidence for memory of a stimulus it is sufficient that the response depends on the earlier experience, irrespective of whether the response is weakened or strengthened over earlier responses to comparable stimuli.

The strengthening of a response upon repetition, called sensitization, is sometimes observed in such experiments [5], [6] early during exposure to a stimulus, especially in young infants. Sensitization may be the basis for familiarity preference, which is observed as stronger responding to a stimulus that is more similar to the habituation stimulus than to a stimulus that is less similar (see [7] for discussion). One index of sensitization in infant orientation behavior is Spencer-Thompson dishabituation [8], [9]. This is observed when habituation to one stimulus, followed by dishabituation to a new stimulus, is probed by then presenting again the original stimulus. Responses to the original stimulus may then be reinstated. Sensitization is also observed in the preferential looking paradigm, in which two stimuli are simultaneously presented to an infant, one of which is persistent across repetitions, the other is constantly changing [2], [10]. After sufficiently long exposure infants show novelty preference, looking longer at novel stimuli than at the repeated stimulus. Early during such a presentation sequence, however, longer looks at the repeated stimulus are sometimes observed.

Theoretical accounts for habituation and sensitization, starting with the classical Sokolov account [9], [11], [12], postulate that while a perceptual representation is being built, attention to a stimulus is stabilized. Once that representation has been accomplished, attention is inhibited. The HAB model [13] provides a possible neural grounding of these ideas, invoking an interplay between Cortex and Hippocampus. In neural dynamic models, feature dimensions along which stimuli vary are represented by populations of neurons organized in neural dynamic fields [7], [14]. The models account for a broad swath of results in infant perception and cognition based only on the metrics of relevant stimulus features, so at a relatively low level of representation close to the sensory surface without any reference to infant knowledge [7]. Support for this hypothesis comes from predicted and confirmed correlations between the dynamics of habituation and the measures of discrimination or recognition [15].

Perseverative reaching is, perhaps, the other major window into infant cognition [16]. In the classical A-not-B paradigm, a young infant reaching repeatedly to an A location at which a toy is hidden will fail to follow a switch to a B location when there is a delay between hiding the toy and allowing the infant to reach. Although the hidden object may play some role in this paradigm [17], the task is fundamentally a motor selection decision for a reach to either location, not unlike the attentional selection between two stimuli in the preferential looking paradigm. In fact, the perseverative effect can be demonstrated in the absence of the toy in which reaches to A or to B are elicited by merely attracting the infant's attention to either location [18].

In a neural dynamic account for perseverative reaching, movement parameters are represented by neural populations organized in neural dynamic fields [19], [20]. A build-up of activation for the movement to the A location explains perseveration, analogous to how activation is built up in a perceptual field in the Sokolov perspective on habituation. In that analogy, perseveration of motor behavior corresponds to sensitization and familiarity preference in looking behavior.

What about habituation? Is there habituation to movement generation? In this study, we transferred the experimental paradigm of habituation to motor behavior, including an infant controlled habituation phase to a given movement, a test of dishabituation when the movement was changed, and a test of Spencer-Thompson dishabituation when returning to the original movement. We report experimental evidence that toddlers show signatures of habituation, dishabituation and Spencer-Thompson dishabituation in that motor task.

We also provide a theoretical account for these results that unifies the neural dynamic models of visual habituation with the model of motor perseveration and makes it possible to identify shared underlying principles of stabilization of perception/behavior early during experience followed by inhibition of perception/behavior, leading to exploration.

II. EXPERIMENTAL BACKGROUND

In typical habituation experiments an infant is seated in a dimly lit room and presented with a single, salient visual stimulus. Looking behavior of the infant is monitored (or other physiological measures are taken). A sequence of presentations of a habituation stimulus is often infant controlled, so that stimulation ends when infants look away from the stimulus for a certain amount of time. A new presentation cycle is then started, sometimes preceded by a special attention grabbing stimulus that may have an auditory component. Total looking time is estimated live during the experiment. When total looking time falls below a criterion level compared to the average looking time during the first three presentations, presentation switches to a new stimulus which may then be repeated. Sometimes, that stimulus is itself varied, sometimes presentation returns to the initial stimulus.

Motor behavior involves many different processes that reach from perception to motor control. The aspect of motor behavior that may be related to sensitization and habituation is the decision to make a particular movement. This is most readily studied in a selection paradigm such as the toy-less variant of the A-not-B paradigm [18], [21], although even in the classical A-not-B task motor dimensions of the task matter [16].

A hint that the amount of experience of reaching to the A location matters was provided by Marcovitch and colleagues [22], [23]. For different infants, the toy was hidden at the A location for one, for 6, or for 11 trials, before the toy was switched to the B location. Infants assigned to the 11 A-trial condition were less likely to perseverate on the B-trial than those in the traditional 6 A-trial condition. Infants in the 1-trial condition did not perseverate. This outcome was characterized as an inherent U-shaped pattern with infants following the cue to B best for very small and very large numbers of A-trials.

An alternative view would be to consider the good performance at small and at large amount of experience with A as having different origins. At low experience, little activation for moving to A has yet been accumulated and does not compete, therefore, with reaching to B. At large amounts of experience of reaching to A, habituation may have suppressed activation at A, removing competition with reaching to B. That earlier experiment does not rule out the possibility, however, that reaches to A are no longer promoted because of habituation at the level of attention to the A location rather than at the level of the motor system itself [24]. By using only a single motor task at a single location, our study pinpoints habituation to the motor level.

III. MOTOR HABITUATION EXPERIMENT

We transposed the typical infant habituation paradigm to movement generation. Toddlers moved a lever on a box that was oriented to allow either vertical or horizontal movement (see Figure 1). While the lever was being moved, the box emitted music which encouraged toddlers to keep moving the lever. The environment and the box were visually nondescript to minimize both visual distraction and the influence by perceptual habituation.

A. Procedure

Thirty-eight 12-month-old and thirty-eight 15-month-old toddlers were tested. They were randomly assigned to two groups that were habituated either to horizontal or vertical lever movement. In the habituation phase the box was pushed toward the toddlers on a track for a trial duration of 15 s. The trial started as soon as the toddlers' hands were on the handle. Movement time and path of the lever were recorded and displayed in real time. The box was then pulled back out of the toddler's reach for an inter-trial duration of 11.5 s. This cycle was repeated until a maximum of 15 trials or until the habituation criterion was met: Movement time averaged across the last three trials dropped below half the movement time averaged across the first three habituation trials.

For the subsequent test phase the box was rotated by 90 degrees. Toddlers habituated on the horizontal movement direction were tested on the vertical movement and vice versa for toddlers in the vertical group. After two trials in the new orientation the box was rotated back to its original orientation for additional two test trials. The toddlers watched how the box was rotated for both switches. Trial and inter-trial duration were the same in the test as in the habituation phase.

If the toddlers did not start to move the lever spontaneously once the box was within their range, the parents drew the toddlers' attention to the box or put their hands on the handle. Before the experiment started, the toddlers were given time to get familiar with the situation and the box. This warm-up phase followed strict rules: The parents demonstrated moving the lever twice, put the toddlers' hands on the handle twice and encouraged them to slide the lever themselves. During warm-up, the orientation of the box matched the habituation condition.

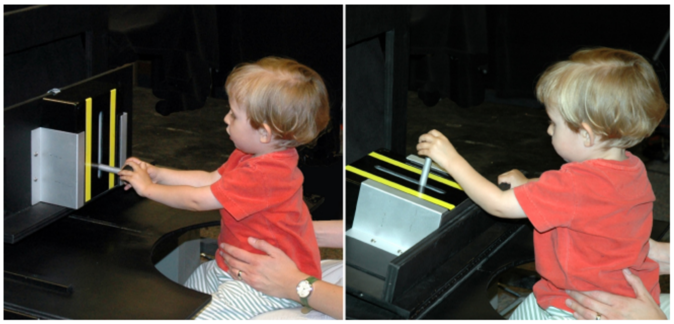

Fig. 1. A box with a lever was presented to toddlers affording either vertical or horizontal movement. Two yellow stripes indicated the movement direction. While the lever moved, the box played music. Toddlers were habituated in one orientation, then the box was rotated for two test trials and finally returned to its original orientation for two additional trials.

B. Data reduction

In general, toddlers started and stopped moving the lever several times during a trial. The movement times and movement paths of each of those episodes were summed. We also analyzed the number of movement episodes, and the peak velocities, and obtained an estimate of looking time at the box based on observer rating. In this short report, we focus only on movement time.

C. Results

The mean movement times of the first and the last three habituation trials as well as of the test trials are shown in Figure 2 for two age groups (12 or 15 months) and two habituation conditions (vertical or horizontal). Figure 2 reveals that movement time decreases over the habituation trials, which is evidence for habituation. Testing at a new movement direction leads to an increase in movement time, evidence for dishabituation. However, movement times are not as high as in the first habituation trials. Dishabituation is significant (p-value < 0.05) for each age group and habituation condition in the first and second test trial. This was determined by performing t-tests that compared movement times of the test trials with the respective movement times of the last habituation trial for each age group and habituation condition. When returning to the original movement direction on the third test trial, movement times were still higher than during that last habituation trial, evidence for Spencer-Thompson dishabituation. Spencer-Thompson dishabituation was significant for all groups and conditions except for 12-month-olds in the vertical condition. On the fourth test trial Spencer-Thompson dishabituation was only significant for the 15-month-olds in vertical and 12-month-olds in horizontal condition.

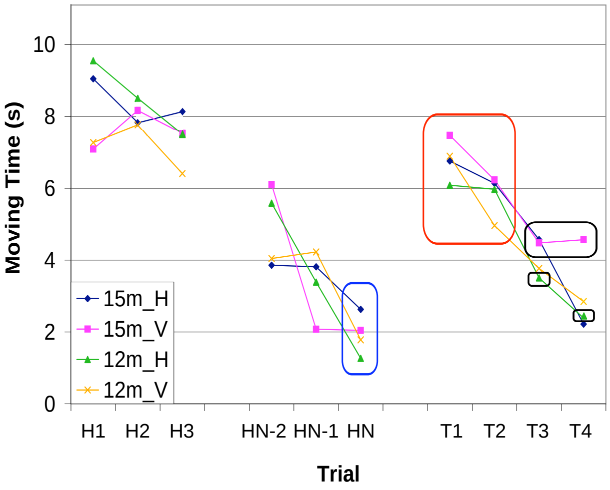

Fig. 2. Experimental data of the motor habituation experiment: Movement times of the first three (H1, H2, H3) and last three habituation trials (HN-2, HN-1, HN), as well as the test trials (T1-T4). Mean movement times are shown for the two age groups (12 or 15 months) by habituation condition, horizontal (H) or vertical (V) movement direction. The red box marks significant dishabituation (significant difference over last habituation trial, HN), the black boxes significant Spencer-Thompson dishabituation (significant difference over the last habituation trial). The blue box marks the last habituation trials as reference values.

IV. THEORETICAL BACKGROUND

To link motor habituation to perceptual habituation and to perseverative reaching, we provide a neural process model within the framework of Dynamic Field Theory (DFT) [25]. This is the language in which earlier theoretical accounts for perceptual habituation [7], [14] and perseverative reaching [19] were formulated. DFT models account for perception and motor behavior through activation patterns in neural populations that are linked to the sensory or motor surfaces. Perceptual representations receive inputs from the sensory surfaces through connectivity that extracts relevant feature dimensions such as visual space, orientation, visual motion direction, texture, or color. Populations of neurons tuned to such features form neural fields over the respective feature dimensions. Motor representations project onto the motor system bringing about a range of different movements characterized by movement parameters such as movement direction, extent, or direction of force. Populations of neurons tuned to such parameters form neural fields over the respective motor dimensions.

Activation in neural fields evolves in time, described by a neural dynamics under the influence of input. Not all of that input comes from the forward connectivity from the sensory surface or other fields. Recurrent neural interaction within neural fields are the dominant contribution to the neural dynamics. As a result, localized patterns of activation are stable activation states. They represent particular values of the feature dimensions or movement parameters through their location. Local excitatory interaction stabilizes such peaks (or blobs) against decay. Inhibitory interaction across the field, mediated by inhibitory interneurons, stabilizes peaks against diffusive spread.

Neural interaction is responsible for decision making in DFT. Only activation that passes the threshold of a nonlinear sigmoidal function contributes to neural interaction and is passed on to other neural populations and ultimately the motor system. As a result, supra-threshold activation peaks arise in an instability, when increasing input drives the sub-threshold activation pattern through the threshold at some location in the field. The sub-threshold activation pattern becomes unstable and excitatory interaction drives the now positive activation toward a stable activation peak. The peak reflects a detection decision: The field has detected significant localized input. When multiple locations in the field are driven by input, global inhibitory interaction may impose that only one peak is formed. That peak reflects a selection decision. Detection and selection decisions are the neural mechanism through which DFT models account for the decisions to fixate on a stimulus in models of habituation or for the selection of a movement target in perseverative reaching.

The simplest form of learning in DFT is the laying down of a memory trace at locations at which a supra-threshold peak has formed. The dynamics of the memory trace is slower than the neural dynamics itself, although not by much. Memory traces in excitatory activation fields have been used to account for pre-trial effects [26], for perseveration [19], and for the role of spontaneous reaches to B [20]. Memory traces in inhibitory fields (of interneurons) have been used to account for selective adaptation [27], habituation [7], [15], and preferential looking [28].

V. MOTOR HABITUATION MODEL

The DFT model of motor habituation (Figure 3) applies the core principle of DFT models of visual habituation [14], [15] to a neural representation of motor intentions [19].

The model consists of a pair of excitatory and inhibitory neural fields defined over movement direction, x, which in the simulations takes on the values $x = \mathrm{H}$ and $x = \mathrm{V}$ for the horizontal and vertical movement directions, respectively. The excitatory movement planning field represents an intention to make a particular movement by a supra-threshold peak. In this simple model, the processes of movement generation are not further elaborated (see [29] for a more complete account). The movement planning field receives three forms of perceptional input. Task inputs reflect the movement direction afforded by the box when it is in reaching space, s_H, or s_V. The reward input, s_R, reflects the reinforcement of motor intention from the sound effect obtained while moving the level. This input is applied whenever activation in the movement planning field is above threshold (modeling that a movement is actually performed and the box plays the music). When the task input is applied but no supra-threshold peak forms in the movement planning field, an additional "attention getting" input, s_A, is applied which helps push activation through the detection instability. This input models the parents' intervening by drawing attention to the box when the toddlers' did not begin to move the lever on their own after the box was pushed close.

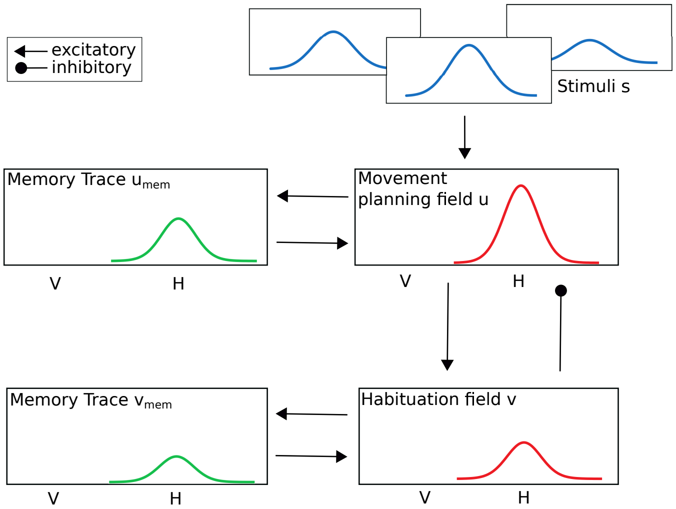

Fig. 3. Sketch of the DFT model of motor habituation. The movement planning field, $u(x)$, and habituation field, $v(x)$ (red) are defined over movement direction, x, sampled in the experiment at horizontal (H) or vertical (V) movement direction. Either field has an associated memory trace (green). The movement planning field receives perceptual inputs, $s(x)$ (blue) that reflect the movement direction afforded by the box. The movement planning field excites the habituation field and is conversely inhibited by the habituation field. The presence of a peak in the movement planning field indicates that a movement is being generated, with the location of the peak specifying the movement direction.

The movement planning field is selective, reflecting that only one movement can be performed at a time. Its memory trace, $u_\mathrm{mem}(x,t)$ evolves on a slower timescale and keeps track of the history of planned movements. It provides excitatory input back into $u(x,t)$, facilitating response at the corresponding field location. The movement planning field provides excitatory input to the habituation field, $v(x,t)$, which in turn inhibits the movement planning field. The habituation field also builds a memory trace, v_mem, that provides excitatory input back to v, leading to increased levels of inhibition at activated locations over time.

The dynamics of u and v are given by the following equations:

$$\begin{aligned}\tau_\mathrm{u}\dot{u} = &-u(x,t) + h_\mathrm{u} + s(t,x) + \int k_\mathrm{uu}(x-x')g(u)\,\mathrm{d}x' \\ &- \int k_\mathrm{uv}(x-x')g(v)\,\mathrm{d}x' \\ &+ \int k_{\mathrm{uu}_\mathrm{mem}}(x-x')g(u_\mathrm{mem})\,\mathrm{d}x' + q\xi_\mathrm{u}(x,t), \\ \tau_v\dot{v} = &-v(x,t) + h_\mathrm{v} + \int k_\mathrm{vu}(x-x')g(u)\,\mathrm{d}x' \\ &+ \int k_{\mathrm{vv}_\mathrm{mem}}(x-x')g(v_\mathrm{mem})\,\mathrm{d}x' + q\xi_\mathrm{v}(x,t),\end{aligned} \tag{1}$$

with the time scales, τ_i, resting levels $h_i < 0$ and the sum of stimulus inputs $s = \sum_k s_k$, with $i = \mathrm{u}, \mathrm{v}$ and $k = \mathrm{H}, \mathrm{V}, \mathrm{A}, \mathrm{R}$. Independent Gaussian white noise, $\xi_i(x,t)$, with strength q is added at all field locations. Lateral interactions are determined by kernels k_{ij} (see below), where the first index corresponds to the target of the projection and the second to its origin ($j = \mathrm{u}, \mathrm{v}, \mathrm{u}_{\mathrm{mem}}, \mathrm{v}_{\mathrm{mem}}$). The sigmoid function $g(u) = 1/(1 + \exp(-\beta u))$ determines that only field locations with sufficient levels of activation generate non-zero output.

The memory trace evolves on a slower time scale, τ_{build}:

$$\begin{aligned} \dot{u}_{\mathrm{mem}} =& \tau_{\mathrm{build}}^{-1} \left[-u_{\mathrm{mem}}(x,t) + g(u) \right] g(u) \\ & - \tau_{\mathrm{decay}}^{-1} u_{\mathrm{mem}}(x,t) \left[1 - g(u) \right], \end{aligned} \tag{2}$$

only while there is a peak of activation at any location in the field (here the movement planning field u). In the absence of any supra-threshold activation in the field, the memory trace remains constant: $\dot{u}_{\mathrm{mem}} = 0$. The memory trace generically has a faster time scale for building, τ_{build}, than for decay, τ_{decay} (this decay is effectively competitive as it occurs only while other field locations are above threshold). An analogous dynamics governs the habituation memory trace, v_{mem}, of the habituation field.

Stimulus inputs, $s_k(x)$, are modeled as Gaussian functions:

$$s_k(x) = \frac{a_k}{\sqrt{2\pi}\sigma_{\mathrm{exc}}} \exp\left\{ -\frac{(x - x_0)^2}{2\sigma_{\mathrm{exc}}^2} \right\}, \tag{3}$$

centered on $x_0 = \mathrm{H}$ or $x_0 = \mathrm{V}$ for horizontal or vertical movement respectively, with width σ_{exc}, and amplitude a_k. The interaction kernels are given by:

$$k_{ij}(x - x') = \frac{c_{ij}}{\sqrt{2\pi}\sigma_{ij}} \exp\left\{ -\frac{(x - x')^2}{2\sigma_{ij}^2} \right\} + c_{ij,\mathrm{glob}}. \tag{4}$$

The Gaussian models local interaction or coupling with width σ_{ij}, and strength, c_{ij}, the constant models global interaction with strength, $c_{ij,\mathrm{glob}}$. For $i = j$, these kernels model intra-field interaction, for $i \neq j$, they model coupling across fields.

Parameter values were constrained by the following elements of the experimental procedure and assumptions about the results: (1) The amplitude of both task inputs, s_{H} and s_{V}, is chosen such that input alone is not strong enough to cause supra-threshold activation in u. Thus, a peak in the movement planning field forms only with additional input from the memory trace or the attention input. This models the experimental fact that toddlers only moved the lever after the warm-up phase, encouraged by their parents and after listening to the music by watching their parents move the lever. (2) The strength of inhibition from the habituation to the movement planning field, c_{uv}, is greater than that of all other inputs to it except for the attention input. Activation in the habituation field is thus able to suppress activation in the movement planning field below threshold. This accounts for the fact that, without renewed encouragement from their parents, toddlers stopped moving the lever after some trials, even if the box was still within reach. (3) The strength, $c_{\mathrm{uu}_{\mathrm{mem}}}$, of excitatory input to the movement planning field from its memory trace, is less than the absolute value of the resting level, $|h_{\mathrm{u}}|$. This accounts for the fact that toddlers would not try to move the lever while it is out of reach. (4) The memory trace, v_{mem}, of the habituation field grows more slowly than the memory trace, u_{mem}, of the movement planning field, but it decays faster. As a result, the faster memory trace, u_{mem}, is predominant in early trials, enabling sensitization. The faster decay of v_{mem} models Spencer-Thompson dishabituation observed in the experiment. (5) The coupling kernel from v_{mem} to v is broader than from u_{mem} to u with a global component, $c_{\mathrm{vv}_{\mathrm{mem}},\mathrm{glob}} > 0$. This makes that habitation generalizes across all movements, but is strongest for the movement experienced. This models that the movement times on the test trials are shorter than movement times on the first habituation trials. (6) To make the movement planning field selective, it has global inhibition $c_{\mathrm{uu},\mathrm{glob}} < 0$. All other global parameters are set to zero.

VI. SIMULATIONS AND RESULTS

The motor habituation model was implemented for numerical simulation using the Matlab framework COSIVINA [30] for dynamic field architectures. The motor habituation paradigm was also encoded within this framework, closely mimicking the experimental procedure described in Section III. Gaussian task input, s_{H}, for the horizontal movement direction was presented in a sequence of trials. The program added attention input when activation in u did not reach threshold within 5 s. Once activation reached threshold or the attention input was applied, the trial started and the task input remained for 15 s. When activation at H became positive, the reward input was added and any attention input was removed. At the end of the trial, all stimulus inputs, s, were removed for an inter-trial period of 12 s. On the first habituation trial, attention input was applied simultaneously with the task input, a form of modeling the warm-up phase. Figures 4 and 5 show exemplary time courses of stimulus inputs and activation levels in both fields at the locations at which horizontal and vertical movement direction are encoded, respectively.

Supra-threshold activation in the movement planning and habituation fields drives growth of their memory traces, which leads to an earlier response in the next trial. The excitatory memory trace, u_{mem}, grows faster than the inhibitory memory trace, v_{mem}, so that in early trials (trials 2 and 3 in Figure 4) the movement planning field, u, goes through the detection instability without attention input. This captures the experimental observation that in those trials, toddlers moved the lever spontaneously. In later trials (trials 6 to 8 in Figure 4), inhibition from the habituation field has grown and suppresses activation in the movement planning field, u, below zero before the trial ends. This captures the experimental observation that toddlers tended to stop their movement before the trial ended and the box was pulled back.

The total time during which activation in u is above zero is an estimate of movement time. The habituation phase ends after a maximum of 15 trials or when the habituation criterion has been met, that is, when movement time of the last three

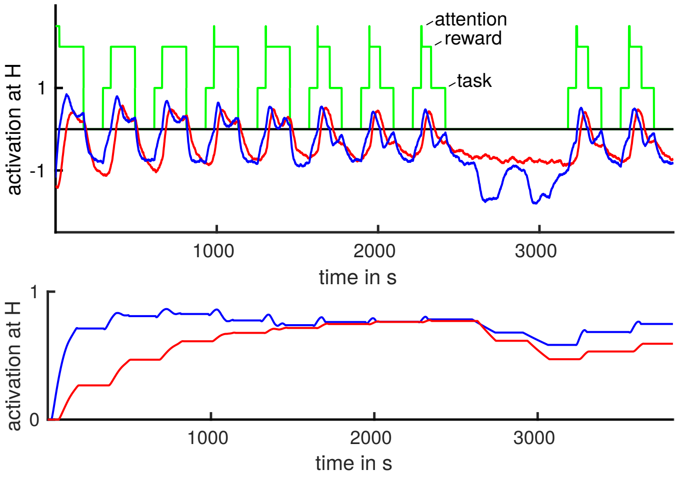

Fig. 4. Time courses of: (Top) activation of stimulus inputs (green), movement planning field, u (blue), habituation field v (red); (Bottom) the two memory traces, all at the horizontal movement direction. The task input lasts for 15 s after activation goes through the detection instability. Reward input is added as long as activation is above zero. Attentional input is applied if activation does not become positive within the first 5 s of a trial. Once activation becomes positive, this input is removed.

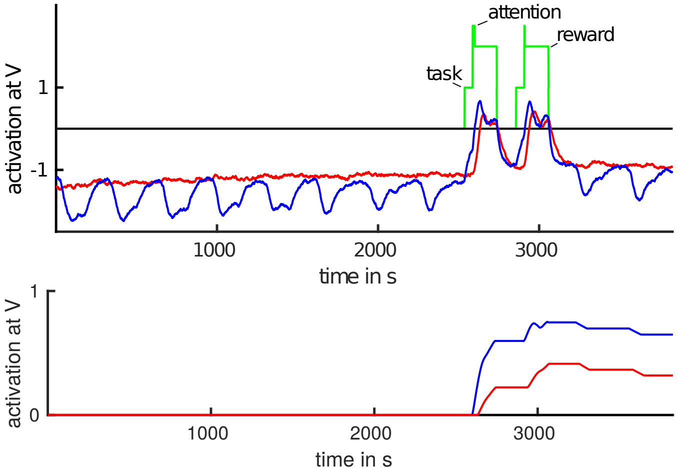

Fig. 5. The same time courses as in Figure 4 are shown for the location of the fields at which vertical movement is encoded.

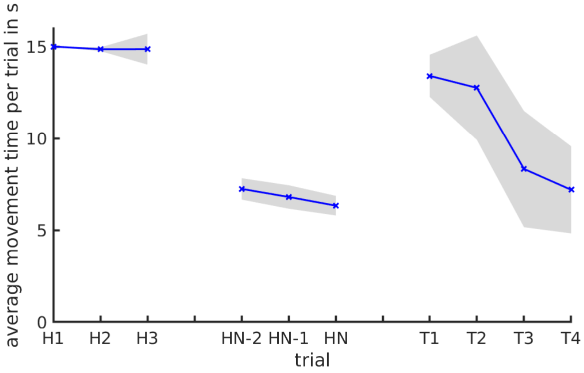

Fig. 6. Mean movement times from the simulation, aligned as in the experimental analysis: The first (H1-H3) and the last three habituation trials (HN-2-HN), the test trials in vertical movement direction (T1 and T2) and the test trials in the original movement direction (T3 and T4) are shown. The standard deviation across repetitions is shown in gray.

trials is less than 50 % of the time of the first three trials. Movement times averaged across 50 repeated simulation runs (each with a new seed of the random number generator to simulate noise but with the same field parameters) are shown in Figure 6 similar as for the experiment (Figure 2).

The model captures habituation through the reduction of movement time in the last three trials of the habituation phase compared to movement time in the initial trials of the habituation phase. In the first test phase, movement time now estimated from activation at the new location increases again strongly, a signature of dishabituation. This is because at the new location, the movement planning field is not yet strongly inhibited by the habituation field. The slight reduction in average movement times compared to the first habituation trials is due to the spread of inhibition from the habituated to the new location. In the second test phase, movement time originates again from activation at the original location. Average movement times are increased in relation to the last habituation trials, a signature of Spencer-Thompson dishabituation. This is due to the faster decay of the memory trace for inhibition, v_{mem}, than for the excitatory memory trace, u_{mem}.

Noise has different effects in different phases of the simulation, revealing differences in stability. Noise is most effective, when the system is close to an instability. Infant dependent elements of the experiment amplify fluctuations. For instance, when activation becomes positive by fluctuation, reward input amplifies such fluctuations. The standard deviation marked in Figure 6 shows that the test phase exhibits larger variance in movement times than in the habituation phase. In the model, this is due to the dependence of activation on the history of movement decisions laid down in the memory traces. Different runs accumulate across habituation different levels of memory traces. This is reflected in different numbers of habituation trials, but hidden from view by the infant-controlled habituation criterion. This then leads to large differences during testing. That the infant-controlled habituation criterion amplifies individual differences is a known issue in experiments as well [5], [7].

Qualitatively, the results are in good agreement with the experimental data shown in Figure 2. The model demonstrates habituation to a repeated movement, dishabituation to a new movement, and Spencer-Thompson dishabituation when the original movement is reinstated. We did not observe any particular limitation to how well the data could fitted quantitatively, but did not try to push quantitative fits beyond what is scene in the Figures. Such quantitative fits may be misleading given the interface between the model and the behavior from which the data derive. In the model, supra-threshold activation signifies an intention to move, but the actual generation of motor commands and activation of muscles etc are not addressed in the model. In light of these processes of movement generation, an exact one-to-one match of intention to move and observed movement time is not expected. What the model shows is, instead, that the overall structure of habituation, dishabituation and Spencer-Thompson dishabituation can be explained by the build-up of activation and inhibition in dynamic neural fields that represent movement intention at the relatively low level of the movement parameter ”direction”.

VII. Discussion

We presented experimental evidence for habituation in a motor task. A neural dynamic field model accounts for the observed habituation to a specific movement, for dishabituation when the movement is changed and Spencer-Thompson dishabituation, when the original movement is probed again. The intention to move in a given direction is represented by supra-threshold peaks of activation in a neural dynamic field that is dominated by neural interaction, both excitatory within the movement field, and inhibitory from a field of inhibitory interneurons. Memory traces in either field lead to inter-trial effects. Habituation is due to the build up of an inhibitory memory trace.

The observed motor dishabituation reflects a form of novelty preference that is induced by habituation. After habituation the novel movement is acted on more strongly than the familiar (=repeated) movement. Familiarity preference would result from the excitatory memory trace: After limited amounts of habituation, the system should act more strongly on familiar than on novel movements. We demonstrated this prediction in simulations of the model, in which we switched to a novel movement parameter early vs. later during habituation.

We propose that the perseveration observed in motor decision tasks like the A-not-B paradigm is an index of such familiarity preference. After limited experience with one movement, when given a choice, the system is biased toward the familiar movement. The observation of Marcovitch and colleagues [22], [23] that perseveration is reduced after prolonged experience of reaching to the A location is, in this interpretation, caused by habituation to the corresponding movement!

Formally, the motor habituation model accounts for perseveration. In fact, if the movement parameter is interpreted as the movement direction of the hand toward objects, the excitatory portion is analogous to the classical DFT model of A-not-B [19]. With the habituation field added in, it accounts for the role of prolonged A trials [22]. An analogous A-not-B experiment for the experimental setting we modeled could be imagined, for instance, by allowing a knob or joystick to be moved in both vertical and horizontal directions. One movement could be demonstrated before each trial, followed by a switch to the other movement after a varied number of trials. The prediction would be that after a few trials, toddlers would tend to perseverate, especially if a delay was imposed between demonstration and action. After more trials of experience, toddlers would follow the demonstration and switch to the new movement. Perseveration in this sense was observed in a pilot study in which toddlers imitated demonstrated actions on a toy. The effect of habituation has not been studied in such an imitation/decision task to date.

The model presented in this paper thus unifies the accounts for habituation and for perseveration. It suggests that there is a universal pattern of early familiarity preference, late novelty preference, early and late referring to how much experience infants or toddlers have with a behavior. This pattern would be common to perception and movement. In fact, it may be common to any form of decision making.

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