We investigated the ability of humans to adapt to a novel environment by kinematic transformation. This adaptation was studied via behavioural experiments using a robotic manipulandum – a system designed to arbitrarily generate virtual force fields against a human hand and subsequently record the hand’s trajectory. By repeating motor tasks, this study’s participants gradually learned to move correctly under a newly experienced force field, such as rotating in a clockwise direction. However, each participant’s motor memory was destroyed if he/she experienced an opposing force field (e.g., in a counterclockwise direction) immediately after learning the initial movement, which is known as retrograde interference. In some previous studies, it has been considered that by presenting sensory cues to highlight the difference in two opposing force fields, participants can learn both force fields independently without interference. In this study, we investigated the functionality of olfactory cues – specifically lemon and lavender odors – in reducing retrograde interference. Forty-five university students participated in an experiment using a robotic manipulandum. Our results have shown that the presence of lemon odor reduces the destruction of motor memory, while that of lavender did not, suggesting that odors can enhance simultaneous motor learning but the effect depends on the type of odor used.

Keywords: olfactory stimuli, motor learning, motor memory, retrograde interference, robotic manipulandum

1. Introduction

Humans can memorize multiple movement patterns suitable for different dynamic and kinematic transformations. For example, humans can immediately adjust movement patterns depending on shoes, such as high heels and runners. This ability to memorize various dynamic and kinematic transformations is called motor memory. In fact, the motor memory was first discussed in a study by Brashers-Krug et al. [1], in which participants learned arm-reaching tasks with unfamiliar force fields generated by a robotic manipulandum. Due to the force fields, the participants’ arm trajectories were initially curved but gradually became straight as the participants learned. The motor tasks were consolidated about four hours after the learning, which the participants were able to retain in a very long temporal interval (at least 5 months) [2]. Before the consolidation, however, if a participant experienced a contradicting motor task, e.g., a task with a force field opposite to the force field used for the directly preceding task, consolidation did not occur. Such a result is called retrograde interference [2–8].

Understandings of the mechanisms underlying retrograde interference can clarify the factors essential to efficient multiple motor-task consolidations. The processes of consolidation and retrograde interference were studied in regards to the ABA paradigm with robotic manipulanda, in which motor tasks in two contradictory force fields were learned in an A-B-A order [1–3, 5, 7–12]. Some researchers suggested that using sensory cues to highlight the differences between two opposing force fields can allow participants to independently learn tasks related to the force fields without experiencing retrograde interference [8, 13–16]. For example, in one study, a robotic manipulandum was used by Cothros et al. [12], who displayed an image of a hand grasping an object when participants performed motor task A in a clockwise force field. Similarly, the researchers showed an image of a hand releasing an object when participants performed contradicting task B in an counterclockwise force field. These images reduced retrograde interference. With the ABA paradigm in particular, different types of cues were tested, but the results were mixed. Cursor colors [12, 13, 17, 18], background colors [17], haptic stimuli [7], and cue locations [19] were insufficient in regards to reducing retrograde interference, while motor task variations, such as different ways to grasp a handle [13], and workspace locations [17] were sufficient. To summarize, those previous studies suggested that arbitrary cues that do not have clear links to motor tasks, such as colors, do not provide contextual information about the tasks, while cues directly relevant to task-related information, such as workspace cues, tended to be sufficient for reducing ret-
rograde interference [17]. However, such direct cues typically need close physical relationships with studied motor tasks, so that they can have unwanted effects on the motor tasks. For example, the way a participant grasps a handle [13] directly changes motion patterns and thus leads a qualitative change from an intended motor task.

While various sensory modalities, e.g., haptic [7, 13], auditory [20], and visual [12, 13, 17, 18], were tested by some studies, we firstly examined olfactory cues in regards to reducing retrograde interference. In a different research context, olfactory cues are arbitrary to motor tasks without having any direct physical links, so that they will not cause qualitative changes from an intended task. Olfactory cues are known to affect movement patterns. In one series of experiments [21–25], the cross-modal effects of olfactory stimuli in regards to finger shapes involved in grasping objects were examined. When participants grasped small objects, e.g., strawberries, in the presence of the odors of larger objects, e.g., oranges, the participants’ finger shapes for grasping the small objects were similar to the finger shapes needed for grasping the larger objects. These studies supported our hypothesis, which was that olfactory stimuli could affect movement patterns.

Based on previous studies [1, 2, 5–8, 10–12], we conducted behavioural experiments using a robotic manipulandum and the ABA paradigm to test olfactory cues can reduce the retrograde interference. A total of 35 university students participated in the experiment. These participants were asked to learn arm-reaching tasks with unfamiliar force fields. To test whether olfactory cues were effective regardless of odor type, we used two odors, lemon and lavender, which have opposing effects on human moods. In practical aromatherapy, the odor of lemons functions as a stimulant odor, to heighten the mood and enhance mental and physical task performance [26–30], while the odor of lavender functions as a relaxant [26, 29, 31].

Retrograde interference was evaluated normally using after-effect sizes, which are the trajectory errors that occur after force fields are changed [1]. Shortly after switching the force field (e.g., switching the force field from counterclockwise to clockwise), the participant experiences unexpected forces. Thus, the participant pushed the handle too hard, causing a huge error instead of a straight push trajectory; this error is called an after-effect [1, 2]. It was hypothesized that if sensory cues function as contextual reminders of which force field will be presented, then the sizes of after-effects may be smaller than they would be without any contextual cues. Our experiment showed that the presence of both lemon and lavender odors reduces after-effects. This suggests that odors have positive effects in regards to reducing the retrograde interference of contradicting motor tasks, regardless of odor type.

Previous studies used two different sensory stimuli that were alternatively presented with respective motor tasks, e.g., a red background color for task A and a blue background color for task B [17]. However, our participants experienced only one olfactory stimulus (either a lemon odor or a lavender odor), in which motor task A was linked to the presence of an odor (lemon or lavender) and motor task B was linked to the absence of odors. Although this experimental setup was different from previous studies, the hypothesis was shared that if a motor task is linked to a sensory cue, the motor task is memorized without retrograde interference. In the study, we adopted a simplest setup, which we expected is the first step to examine the functionality of odor cues.

The organization of this paper is as follows. First, in Section 2, we detail the environment and the methodology used for the study. Second, in Section 3, we include the results and an analysis of them. Third, in Section 4, we consider the effects of using olfactory stimuli as contextual cues, and we suggest future applications of olfactory stimuli to motor learning.

2. Methods

2.1. Participants

A total of 35 participants were recruited from the Tokyo University of Agriculture and Technology. The subjects comprised both undergraduate and graduate students. All were male and right-handed; handedness was clarified using the Edinburgh Handedness Inventory [32]. None of the participants had been part of motor learning experiments with force fields. Two participants did not pass an olfactory test detailed below, and eight did not complete the experiment due to mistakes in the procedure. We analyzed the remaining 35 participants’ responses (mean age = 21.9 ± 2.20 S.D.).

We used four participant groups: lemon-experimental (n = 10), lemon-control (n = 9), lavender-experimental (n = 8), and lavender-control (n = 8). A ‘between subjects’ design was used instead of a ‘within subjects’ design, which could have been more statistically powerful. The reason to use between subjects design was because, once they learned motor tasks under force fields, participants are known to retain the motor memory in a very long temporal interval (at least 5 months) [2]. Therefore, the participants needed to be naive to such motor tasks, which made a within-subject design inappropriate.

This study was carried out in accordance with the recommendations of the ethical committee of the Tokyo University of Agriculture and Technology (project number 28-28) with written informed consent from all subjects. All subjects gave written informed consent in accordance with the Declaration of Helsinki. The protocol was approved by the ethical committee of the Tokyo University of Agriculture and Technology.

2.2. Manipulandum

The experiment involved a robotic manipulandum that was used to measure and regulate hand movements (picture: Fig. 1(a), and illustration: Fig. 1(c)) [2, 5, 8, 10, 11, 20]. The manipulandum had an opaque white screen on which visual stimuli were displayed using an liquid crys-
eral display (LCD) projector mounted on the ceiling above the screen (Fig. 1(a)). Beneath the screen, the manipulandum had a handle that could be moved on a horizontal plane; the handle was connected to two direct-drive linear slider motors with \( x - y \) directions in a horizontal work space that could generate pseudo force fields. Each participant sat on a chair 15 cm from the front of the manipulandum and grasped the handle with his right hand. The software program used to control the system was written in the C language. The program regulated and recorded the movement of the handle and displayed visual stimuli on the screen (detailed later in Fig. 2). The control cycle of the manipulandum was set to 500 \( \mu \)s. The motors were all linear actuators, in which maximum displayed forces were set to 599 N for the horizontal axis (NSK, YB3) and 197 N for the vertical axis (NSK, YA2).

2.3. Force Field

The manipulandum generated three types of force fields: viscous curl force fields rotating either in the counterclockwise or clockwise direction, as well as a null force field, which were regulated as follows:

\[
\begin{bmatrix}
  f_x \\
  f_y
\end{bmatrix} =
\begin{bmatrix}
  0 & D \\
  -D & 0
\end{bmatrix} \begin{bmatrix}
  v_x \\
  v_y
\end{bmatrix}, \ldots \ldots \ldots (1)
\]

where \([f_x, f_y]\) denotes the force vector assigned to the handle. The force vector was determined by the velocity of the handle \([v_x, v_y]\) to imitate viscosity. \( D \) is a constant taking a value of \( \pm 30 \) or 0 Ns/m. \( D = 30 \) generated a clockwise force field, while \( D = -30 \) generated a counterclockwise force field. \( D = 0 \) created a null force field. In the remainder of the paper, we use CCW and CW as abbreviations for the counterclockwise and clockwise force fields, respectively. The null force field condition indicates a situation in which the handle does not receive any external forces, e.g., frictions. To realize the null force field, the handle had a force sensor that could generate a force to compensate for that added to the handle.

2.4. Motor Task Procedure

The participants were instructed to move the handle, to which a force field was applied, to make a cursor on the manipulandum’s screen reach a target position (illustrated in Fig. 1(c)). The participants were required to move the handle in a path as straight as possible in 500 ms. They were instructed to use their arms only, but not their shoulders or upper halves of bodies. They received visual feedback that was projected onto the manipulandum’s screen with a black background (Fig. 1(c)). The handle’s target position and its current position were denoted by yellow circles with 2.5 cm radii, while the handle’s initial position was denoted by a blue circle with a 3.5 cm radius. One arm-reaching movement is regarded as one trial. One trial was considered finished if the handle position on the screen successfully reached the target or if 500 ms was passed but the cursor did not reach the target.

Figure 2 illustrates the overall procedure. Before each trial began, a blue circle indicating the handle’s initial position was displayed (Fig. 2(a)). Then, 1 s after the blue target marker appeared 15 cm behind the initial position. (c) A beep sound prompted the start of the trial. (d) The target was displayed for 500 ms, within which the participants were asked to complete the trial. If they succeeded, the word “success” was displayed. (e) After finishing the trial, the handle was automatically returned to the initial position.
Table 1. Experimental phases. Participants experienced the following four experimental phases in sequence: practice, learning, interference, and test. Based on the experimental phases, the manipulandum generated force fields rotating either in counterclockwise (CCW) or clockwise (CW). For each experimental groups, odors stimuli were presented; “lemon” and “lavender” denote presentation of either lemon or lavender odors, while “no odor” indicates no odor from a face mask (sham stimulation).

<table>
<thead>
<tr>
<th>Phase</th>
<th>Practice</th>
<th>Learning</th>
<th>Interference</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force field</td>
<td>null</td>
<td>CCW</td>
<td>CW</td>
<td>CCW</td>
</tr>
<tr>
<td>Number of cycles</td>
<td>40</td>
<td>150</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Odor condition</td>
<td>Lemon-experimental</td>
<td>no odor</td>
<td>lemon</td>
<td>no odor</td>
</tr>
<tr>
<td></td>
<td>Lemon-control</td>
<td>no odor</td>
<td>lemon</td>
<td>lemon</td>
</tr>
<tr>
<td></td>
<td>Lavender-experimental</td>
<td>no odor</td>
<td>lavender</td>
<td>no odor</td>
</tr>
<tr>
<td></td>
<td>Lavender-control</td>
<td>no odor</td>
<td>lavender</td>
<td>lavender</td>
</tr>
</tbody>
</table>

2.5. Experimental Conditions

As is summarized in Table 1, four phases of the experiment—practice, learning, interference, and test—were conducted sequentially as follows.

1. The practice phase was composed of 40 trials under the null force field. This allowed the participants to become used to handling the manipulandum (the column “Practice” in Table 1).

2. The learning phase consisted of 150 trials under the CCW force field. This phase was started immediately after the practice phase, during which the olfactory stimuli (either lemon or lavender) was presented (the column “Learning” in Table 1). Afterwards, the participants took 5 min rest while the air of the room was vented.

3. The interference phase consisted of 150 trials under the CW force field (the column “Interference” in Table 1), which were started after the 5 min of rest. For the experimental conditions (both lemon and lavender), no odors were presented (sham stimulation), while the control groups had the corresponding olfactory stimuli (either lemon or lavender).

4. The testing phase was conducted 24 hours after the beginning of the practice phase, with 150 trials being under the CCW conditions (the column “Test” in Table 1). This 24 hours interval was intended to ensure that the interference phase became consolidated [2, 4]. In both the experimental and control conditions, the olfactory stimuli were present.

2.6. Olfactory Function Testing

Before conducting the experiment, the participants were tested to determine whether their olfactory perceptions functioned properly enough to complete the experiment. We used a T&T olfactometer, which is commonly used in Japan to diagnose smell disorders [33] (Daiichi-Yakuhin, Tokyo, Japan). It is composed of five test odors: 1) β-phenylethylalcohol (rosy; C₆H₅CH₂CH₂OH; 63.1 mg/mL), 2) methlycyclopentenolone (caramel; (CH₂)₂(CO)₂CH(CH₃); 79.2 mg/mL), 3) iso valeric acid (sweat; (CH₃)₂CHCH₂COOH; 100 mg/mL), 4) γ-undecalactone (peach; (CH₂)₂CH(CO₂)C₇H₁₅;
251.4 mg/mL), and 5) skatole (fecal odor; C₃H₆NCH₃; 397.5 mg/mL). For each of the five odorants, participants were given five strips of papers, two of which had 1 cm dipped into an odontant diluted with liquid paraffin, while the remainder were soaked in an odorless contrast solution (liquid paraffin). The participants were asked to choose the two strips out of the five that they thought had been soaked in the odorant. The participants who answered all of the questions correctly were analyzed further.

2.7. Olfactory Stimuli

For the olfactory stimuli, we used essential oils that were made for use in herbal remedies, i.e., the oils were not made for medical nor experimental uses but for general uses in daily life. The lemon essential oil was obtained from Caris Seijo (http://www.charis-herb.com; Tokyo, Japan) and the lavender essential oil was obtained from MUJI (https://www.mujji.net; Tokyo, Japan). Fig. 1(b) shows the method used to provide the participants with the olfactory stimuli. Each participant wore a mask that was 175 mm × 90 mm. A small gauze patch that was 5 mm × 5 mm was stuck to the mask. To give odor stimuli, each participant received a patch with 5 mL of the lemon essential oil or 5 mL of the lavender essential oil, respectively. For sham stimuli, each participant received a patch without any essential oil. To keep the experiment room odorless, the room was vented using an air purification system, and windows were opened both on a regular basis and just before each participant started the experiment. Moreover, inside the room, there were no objects that could generate smell other than the essential oil patch that was being tested.

Habitation can occur with odor perception within only a few minutes at both subjective and receptor levels [34]. Thus, the most appropriate method for applying olfactory cues needed to be investigated. As previous studies suggested [12, 17], motor errors can converge within a participant’s first several trials. We therefore considered olfactory cues at the very beginning of each trial phase the most important in regards to suggesting to the participants which task they were completing.

2.8. Force Channel

The force channel is another index with which to evaluate after-effects. This refers to a special force field that provides a straight channel from the initial position to the goal. The horizontal forces exerted on the handle are regarded as an index of after-effects. This setup allowed us to measure untwisted after-effects by the force field [1, 2, 20]. We adopted the force channel for the lavender condition. Specifically, 15 trials were randomly selected from the 150 trials in the learning and test phases (trials 1, 9, 18, 31, 45, 60, 66, 79, 92, 95, 98, 108, 127, 133, and 145). However, in the first trial, many of the participants failed to move (moving less than 5 mm from the starting position within the 500 ms), and thus, we did not collect sufficient data for the analysis. As detailed in Section 3, after-effects were still observable in the CCW force fields, and this failure did not change our final conclusions. We eliminated the 15 trials with the force channel, and used the 135 remaining trials in our further analysis.

2.9. Cumulated Perpendicular Error (CPE)

As mentioned in Section 1, success in simultaneous motor learning is assessed via the size of the after-effects, which represents the kinematic error in the participant’s hand trajectory as compared to a straight line and is observable just after switching the force field. The size of the after-effects was evaluated using the cumulated perpendicular error (CPE, illustrated in Fig. 1(d)), into which the horizontal distances of the current cursor position from the midline were temporally integrated. CPE assumed the minimum value of 0 when the trajectory was exactly the same as the midline. If the interference phase overwrote the motion pattern acquired during the learning phase, CPE at the beginning of the test phase was expected to be higher. On the other hand, if the participants successfully utilized the olfactory stimuli as contextual cues and retained the motion from the learning phase, CPE would likely remain lower throughout the test phase.

3. Result

Figure 3 shows the average cumulated perpendicular errors (CPEs) for all the participants (Fig. 3(a) is for the lemon odor and Fig. 3(b) is for the lavender odor) for the 150 trials of each block. The y-axis indicates the aver-
age CPEs, and the x-axis indicates the number of trials. CPE gets saturated rather quickly within first several trials, so that Fig. 3 shows only the 150 trials for each trial phase. The learning and test phases for the lavender odor included 15 trials with the force channel; Fig. 3 shows the remaining trials. The error bars in the figure denote s.e.m. The figure shows that CPEs increased immediately after conditions switched, i.e., immediately after the learning switched to the interference phase and after the interference phase switched to the test phase; CPEs decreased afterwards. However, for the lemon-experimental group, CPEs did not highly increase at the beginning of the test phase.

3.1. CPE Model

To evaluate CPE changes, we approximated learning curves using the exponents $y = f(x) = ae^{-bx} + c$. We selected these exponents because current motion errors were considered functions of errors in previous trials [35]. Each initial trial was important in regards to evaluating after-effects; thus, we estimated the initial error $y_1 = f(1) = ae^{-b} + c$ based on the obtained exponents and used $y_1$ for further analyses as an indicator of after-effects.

It should be noted that the after-effects rapidly and smoothly disappeared after trials were repeated, so we used only the first eight trials for approximations. If a participant retained a motion pattern that he/she acquired during his learning phase, the test phase value of $y_1$ was lower than the learning phase value of $y_1$. However, if the participant forgot the motion due to the interference phase, then the test phase value of $y_1$ had no difference than the learning phase value of $y_1$.

When conducting nonlinear regression analysis, we found it difficult to find suitable starting values for convergence. Therefore, we fixed $c$ to the 11 values [0, 0.0005, 0.001, 0.0015, 0.002, 0.0025, 0.003, 0.0035, 0.004, 0.0045, and 0.005]. With the respective values of $c$, we attempted to estimate the rest of the parameters $a$ and $b$, which were performed to reduce the number of parameters, generating good convergence. For each of $c$, we obtained 11 models. Then, we adopted the model with the least residual sum-of-squares to finally estimate $y_1$.

For each odor condition (lemon or lavender), a two-way repeated measures ANOVA was performed by experimental group (experimental or control) and phase (learning or test) with the initial error $y_1$ as an objective variable. Repeated measures were used for phases. All eight statistical groups, i.e., the learning- and test-phase of each lemon-experimental, lemon-control, lavender-experimental, and lavender-control groups, were normally distributed according to a Kolmogorov–Smirnov test.

For the lemon odor, there was a trend towards significance in the interaction between the experimental group and phase ($F(1,17) = 3.04, p = 0.099$). As for the lavender odor, no significant interaction was observed ($F(1,14) = 0.21, p = 0.65$). Although the interaction effect in the lemon odor condition is only a trend towards significance, there is a clear difference from that of the lavender condition with respect to their $p$-values. Given this, exploratory analysis was conducted for simple main effects to compare the $y_1$ values between the learning and test phases for each of the experimental and control groups. Fig. 4(a) shows the $y_1$ for the learning and test phases (the gray and white bars, respectively) averaged across all participants, with the error bars denoting s.e.m. The lemon-experimental group had a significant decrease in $y_1$ ($F(1,9) = 11.11, p = 0.0087$), while the lemon-control group did not have any significant changes ($F(1,8) = 0.54, p = 0.48$). In the lavender odor condition, we did not conduct any further analyses of the simple main effects. As for the main effects, no significant differences were observed by phase ($F(1,14) = 4.17, p = 0.06$) and not by experimental group ($F(1,14) = 0.25, p = 0.62$). To summarize, the lemon odor operated as a contextual cue, while the lavender odor did not. This suggests that some types of odors are effective in reducing retrograde interference, but the effect depends on the types of odors.

3.2. Stability

The results shown in Fig. 4(a) were obtained from the approximation comprising the first eight trials. The following addresses the stability of these results as different numbers of trials were used for the approximation. Fig. 4(b) shows $y_1$ estimates for various numbers of trials. In the figure, the x-axis indicates the number of trials used for the approximation (3–10), while the y-axis shows $y_1$ averaged across all individuals. The black points indicate $y_1$ for the learning phase, while the white points indicate $y_1$ for the test phase. The error bars show s.e.m. The results of a paired two tailed $t$-test for the learning and test phases can be summarized using the following notations: ***: $p < 0.01$ and *: $p < 0.05$.

For all of the conditions (lemon-experimental, lemon-control, lavender-experimental, and lavender-control), the aforementioned tendencies with the first eight trials were observed; namely, significant decrease in $y_1$ in the lemon-experimental condition, no significant difference in the lemon-control condition, and no-significant decrease in $y_1$ under the lavender conditions.

4. Discussion

In this study, we examined the use of olfactory stimuli as contextual cues to prevent retrograde interference. As aforementioned, we conducted behavioural experiments using a robotic manipulandum. In these experiments, participants learned an arm-reaching task with two unfamiliar force fields, and olfactory cues were used to discriminate between the two force fields. Only lemon odor reduced retrograde interference, which was represented using after-effects, while lavender did not. These results suggest that certain olfactory stimuli can function as contextual cues but that the effect depends on the type of odor.

As noted in the introduction, previous studies used two
different sensory stimuli alternatively presented with respective motor tasks [17], while our participants experienced only one olfactory stimulus (either a lemon odor or a lavender odor), in which the motor task A was linked to the presence of the odor and motor task B was linked to the absence of odors. This study’s setup was very simple for examining the effects of odors on retrograde interference. Future research should expand the setup to present two distinct odors to participants, i.e., one odor for task A and one for task B. Furthermore, an experiment could use three or more odors linked to multiple motor tasks. There are many different types of odors, such as lemon (fruity), coffee (roasted), peppermint (herbal), jasmine (floral), and musk (animal), each of which can be used to differentiate between motor tasks. The findings of such studies may be valuable in regards to practical uses, for instance learning multiple motor tasks at one time.

Previous studies have tested various types of sensory cues in regards to reducing retrograde interference. While certain cues that were directly relevant to motor tasks, e.g., workspace locations [17], images of hands [12], and ways to grasp handles [13] were functional, arbitrary cues without clear links to motor tasks were not functional, e.g., colours and textures [7, 12, 13, 17–19]. However, unlike previous studies, we found that olfactory stimuli are functional although the relationships between odors and

Fig. 4. (a) Mean value of $y_1$ averaged across participants of the lemon condition. The black bars indicate mean values of $y_1$ in the learning phase, and the white bars indicate mean values of $y_1$ for the test phase. The error bars show $s.e.m.$ The results of a ANOVA were summarized using the following notation: ***: $p < 0.01$, and n.s. $\geq 0.05$. (b), (c) Mean value of $y_1$, with varying numbers of trials being used for the estimation, for the lemon and lavender conditions respectively. The x-axis indicates the number of trials used, while the y-axis indicates mean values of $y_1$ across individuals. The black points indicate $y_1$ in the learning phase, and the white points indicate $y_1$ during the test phase. The error bars show $s.e.m.$, with the results of the paired t-test being denoted as follows: ***: $p < 0.01$, and *: $p < 0.05$. 

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the motor tasks seem arbitrary. As noted in the introduction, while direct cues could cause an unwanted physical change from an intended motor task, olfactory cues, which have no direct links to the motor task, will not affect it.

In the experiment, the lemon odor showed strong effects on motor learning, while the lavender odor did not have positive effects (Fig. 4(a)). We would like to consider the characteristics of lemon and lavender odors as identified in related studies on olfaction. In practical aromatherapy, lemon has been regarded as a stimulant odor, one that heightens the mood and enhances mental and physical task performance [26–30]. In fact, both human and mouse studies have suggested that lemon essential oils affect the levels of certain neurotransmitters, including dopamine, serotonin, and norepinephrine [26,36]. Specifically, norepinephrine is known to contribute to learning and memory through the modulation of synaptic plasticity [37], which may explain the enhancement of motor learning in our current experiment. In addition, the inhalation of lemon essential oil reduced immobility time in a tail suspension test of mice, meaning that it had an antidepressant-like effect, which indirectly suggests a positive effect on motor skills [36] and is also consistent with our results. On the other hand, lavender is referred to as a relaxant odor that is used to alleviate insomnia, anxiety, nervousness, and melancholy [26, 29, 31]. A study performed by Diego [38] showed that lavender oils induce similar EEG patterns to that seen during drowsiness. While smelling lemon odors kept norepinephrine levels elevated after the administration of a cold pressor, lavender odors produced as low levels of norepinephrine as those produced with water [26]. Because of the absence of the positive effects on norepinephrine, the lavender odor showed a weaker effect on simultaneous motor learning.

This work can be applied to rehabilitation in future. The insights into reducing retrograde interference will allow patients requiring rehabilitation to learn various motion patterns without requiring temporal intervals. In addition, differently from visual cues, olfactory cues are relatively easy to present. While visual cues require a screen, a projector and controlling software to display the cue, olfactory cues require only a mask and a patch with scent, which can be obtained easily and inexpensively. For practical applications, it will be necessary to systematically explore for effective scent to serve as contextual cues, by testing various odorants [34]. Differences in effect may depend on the chemical characteristics of odorants; however, because memory is often retrieved by specific and personal triggers [39], personal preferences may also be worth considering.

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Olfactory Cues to Enhance the Simultaneous Learning of Motor Tasks

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