Sequential Effects in Odor Perception

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Abstract

Introduction Our visual, auditory, and tactile perception is not solely determined by what we process at a given moment in time, but also determined by what we perceived recently. These sequential effects can either be negative (repulsive) or positive (assimilative). Here, we investigated whether such sequential effects also occur in odor perception.

Method Participants rated a sequence of 40 different odors (varying widely in hedonic valence) on four different characteristics (intensity, familiarity, valence, and arousal). For each of these characteristics, we conducted an inter-trial analysis, based on whether the rating on the preceding trial was low or high.

Results We found a positive serial dependence for both odor intensity and familiarity ratings. That is, the rating on the current trial was higher when the rating on the previous trial was high than when the rating on the previous trial was low. We observed no sequential effects for odor valence and arousal ratings.

Conclusion The olfactory system integrates previous stimuli into the current perception of intensity and familiarity.

Implications

The current findings may be relevant for marketing applications and may guide the design and use of olfactory-enhanced virtual and augmented reality systems.

Keywords Sequential effects · Olfactory · Intensity · Familiarity · Valence · Arousal

Introduction

Our recent sensory history affects our subsequent experiences (Pascucci et al. 2019). The existence of such a serial dependence means that the response given on trial t depends on the response given on the preceding trial ($t-1$). In visual perception, for instance, sequential effects occur not only for simple judgements on low-level visual features such as color (Barbosa and Compte 2020), orientation (Fischer and Whitney 2014), and motion (Alais et al. 2017) but also for more complex judgements on facial attractiveness (Taubert et al. 2016b) or the esthetics of paintings (Kim et al. 2019). Similar short-term dependencies have been reported within the auditory (Alais et al. 2015; Jesteadt et al. 1977; Piazza et al.

2018) and tactile domain (Hachen et al. 2020), and even between different sensory modalities (Harvey et al. 2014; Kayser and Kayser 2018; Van der Burg et al. 2015a; Van der Burg and Goodbourn 2015; Wozny and Shams 2011).

Sequential dependencies are known to affect different processes, such as perception (Van der Burg et al. 2013; 2015a; 2018; Van der Burg and Goodbourn 2015), attention (Kristjánsson and Campana 2010; Theeuwes and Van der Burg 2007), decision-making (Abrahamyan et al. 2016; Vinson et al. 2019), memory (Makovski and Jiang 2008), and motor behavior (Wing and Kristofferson 1973). Sequential effects can either be negative or positive. Positive or assimilative sequential effects shift the appraisal of a current stimulus toward the preceding stimulus. For instance, a face is perceived as more attractive after seeing an attractive face, and as less attractive after seeing an unattractive face (Kok et al. 2017; Liberman et al. 2014; Taubert et al. 2016b; Van der Burg et al. 2019; Xia et al. 2016). Negative (repulsive or contrasting) sequential effects shift a percept away from the preceding stimulus. For instance, the perceived orientation of a Gabor patch is shifted away from its orientation on the previous trial (the tilt-after effect; Fritzsche et al.

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2017; Gibson and Radner 1937). It has been suggested that a negative sequential effect reflects a lower-order perceptual process, whereas a positive sequential effect reflects higher-order post-perceptual (e.g., decisional) processes (Fritsche et al. 2017). The finding that positive sequential effects only occur if stimuli are attended or behaviorally relevant while negative sequential effects are independent of attention (Van der Burg et al. 2013; 2018) appears to sort this argument. Further evidence for this hypothesis is the observation that effectively blocking high-level modulatory feedback (i.e., suppressing stimulus awareness) through visual backward masking inverted the sign of a sequential effect, turning a strong assimilative effect into a robust repulsive one (Fornaciai and Park 2019). Furthermore, the suppression of such a repulsive serial dependence by forward masking provides evidence for a local and low-level process that is based on feedforward activation, independent from visual awareness and high-level processing (Fornaciai and Park 2019). Positive and negative sequential effects both have their functional benefits. A positive sequential effect reduces noise and creates a more stable or coherent percept by integrating (or averaging) information over time, while a negative sequential effect facilitates change detection by enhancing perceptual differences (Kiyonaga et al. 2017; Taubert et al. 2016a).

In this study, we investigated whether sequential effects also play a role in odor perception. We therefore analyzed an existing data set (Toet et al. 2019) in which participants consecutively rated 40 different odors (varying widely in hedonic valence) on four different characteristics (intensity, familiarity, valence, and arousal). Using this dataset, previous studies derived (1) a quadratic (U-shaped) relation between mean valence and arousal ratings (Toet et al. 2019), and (2) a network model describing the relation between detection threshold, odor intensity, familiarity, and the affective appraisal (valence, arousal) of odors (Liu et al. 2020). Here, we conducted an inter-trial analysis for each of the four odor characteristics, to investigate whether the ratings on a given trial depend on the ratings on the trials immediately preceding that trial.

To the best of our knowledge, there are no previous studies that investigated the occurrence of sequential effects for intensity, familiarity, valence, and arousal for randomly presented sequences of many different odors covering a wide range of the hedonic scale. Two early studies on sequential intensity judgements for two different odorants (eugenol and acetophenone, and butanol and amyl acetate in Gregson 1983; Gregson and Paddick 1975, respectively) in different concentrations obtained only inconclusive results with small effect sizes and large inter-individual differences. Baird et al. (1996) found a negative sequential effect for the intensity ratings of seven concentrations of pyridine (a basic heterocyclic organic compound with a distinctive, unpleasant fish-like smell), using a repeated random presentation procedure.

Using six pleasant and six unpleasant odors in three different concentrations (36 stimuli in total), Madigan et al. (1994) found no hedonic sequential effect when the pleasant and unpleasant odors were presented in alternating order. Other related studies either used only very few odors or presented the odors in blocks of the same valence. For repeated presentation of two pleasant and one unpleasant odors, Croy and colleagues (2013) found that the valence of pleasant odors remained constant while it increased (shifted toward neutrality) for unpleasant odors. Ferdenzi and colleagues (2014) observed affective habituation (a shift toward hedonic neutrality) after repeated exposure of two different odorants (anise and chocolate). Using eight positive and four negative odors, presented in blocks of four, Nakano and Ayabe-Kanamura (2017) found that unpleasant odors are rated more unpleasant after smelling pleasant odors, but not the other way around (pleasant odors are not rated more pleasant after smelling unpleasant odors).

In sum, previous studies on sequential effects in odor perception did not examine arousal and familiarity, but focused either on intensity or on valence. These studies differed widely in the type of stimuli and the experimental design, making it hard to relate their results. Therefore, we examine sequential effects for a large number and wide range of randomly presented odors and for four characteristics (familiarity, intensity, arousal, and valence) in a single experiment.

Methods

The results reported in this study are obtained from an analysis of experimental data that have been reported before (Toet et al. 2019). For reasons of completeness, we will briefly describe the experimental details here. A more complete description of the experimental conditions is given elsewhere (Toet et al. 2019).

A total of 56 Dutch students (32 females, mean age = 24.3 years, SD = 4.6 years) participated in this experiment. The exclusion criteria were factors that could affect olfactory perception (e.g., diseases, having a cold, smoking, or drinking alcohol) and pregnancy. Participants, as well as the experimenter, were asked not to use perfume, deodorant, or scented clothing on the day of the experiment. All participants signed an informed consent form prior to the experiment. The experimental protocol was reviewed and approved by the TNO Internal Review Board (TNO, the Netherlands: reference 2019–024) and was in agreement with the Helsinki Declaration of 1975, as revised in 2013 (World Medical Association, 2013).

The stimuli consisted of 40 different odor samples, presented in pen-like odor dispensing devices (Hummel et al. 1997), ranging from unpleasant and arousing (e.g., feces, fish), via pleasant and calming (e.g., clove, cinnamon) to

pleasant and stimulating (like peach, caramel; for a detailed description of all odors see Liu et al. 2020; Toet et al. 2019). To ensure the compatibility between the odor samples and to prevent extreme intensity differences, all intensities were kept within about 25% of the mean intensity (Hummel et al. 1997; Liu et al. 2020). All samples complied with the safety standards of the International Fragrance Association (The International Fragrance Association (IFRA), 2019).

Valence and arousal ratings were obtained for each odor using a computer-based graphical EmojiGrid affective self-reporting tool (Toet et al. 2018). The EmojiGrid (see Fig. 1) is a rectangular grid that is labeled with emojis with facial expressions that vary from disliking (unpleasant) via neutral to liking (pleasant) along the horizontal axis (valence), and gradually increase in intensity along the vertical axis (arousal). Users respond by marking the location inside the grid that best represents their affective appraisal of the stimulus. All ratings were scaled to a range between 0 and 100.

Familiarity and intensity of each odor were measured with two single-item questions: “How intense is the scent?” and “How familiar is the scent?”. Participants rated these items by dragging a slider under each question to a value between 0 and 100. The participants were explicitly asked not to attempt to identify the smells since awareness of odor sources may influence their valence, intensity, and familiarity (Ayabe-Kanamura et al. 1998; Distel and Hudson 2001; Ferdenzi et al. 2013; Martinec Nováková et al. 2015; Seo et al. 2008).

During the experiment, the experimenter presented each of the 40 scent pens once for about five seconds at a distance

of about two centimeters from the edge of both nostrils of the participant. The presentation order was randomized over the participants. The participants took one or two sniffs following a verbal command (natural sniffing is known to provide optimal odor perception, see Laing 1983). Immediately after sniffing, the pen was removed and the participants were instructed to rate their affective appraisal (valence and arousal), intensity, and familiarity of the smell (in this order; Groszofsky et al. 2011). After the participant finished the ratings, the next odor was presented. The inter-stimulus interval was on average 22.8 s. The entire experiment lasted about 25 min.

Results

Through inter-trial analyses, we examined whether the ratings on a given trial t depend on the corresponding ratings on the preceding trial (see e.g., Alais et al. 2017, 2015; Van der Burg et al. 2013, 2015b). Thereto, for each of the four odor characteristics measured (valence, arousal, intensity, and familiarity) and for each participant, we first calculated the median rating overall 40 odors (i.e., the neutral rating for each characteristic for a given participant). Note that this was performed for each individual participant, as the overall ratings may vary substantially across the individual participants (see e.g. Ferdenzi et al. 2013). Subsequently, each odor was either labeled “low” or “high” for a given characteristic, if the rating for that particular odor was either $<$ or $\geq$ than the participants’ median rating for that characteristic, respectively. Then, for all participants and each odor characteristic, we binned the data into two bins. One bin contained those trials in which the preceding odor was labeled “low,” and the other bin represented those trials in which the preceding trial was labeled “high.” For each participant, we then calculated the mean rating for each bin. The difference between the means of the “high” and “low” bins then represents the inter-trial effect. Figure 2 depicts the serial dependencies for the mean valence, arousal, intensity, and familiarity ratings. The first trial was excluded from further analyses since we were interested in history effects up to one trial back.

For each characteristic (valence, arousal, intensity, and familiarity), we examined whether the rating on a given trial t depended on the rating on the preceding trial (i.e., a low rating on trial $t-1$ versus a high rating on trial $t-1$) using two-tailed t tests. All statistical analyses were conducted using Just Another Statistics Program (JASP; Love et al. 2019). In the present study, α was set to 0.05. The t tests yielded a significant sequential effect for the intensity and the familiarity ratings, $t(54) = 4.71$, $p < 0.00005$, and $t(54) = 2.92$, $p < 0.01$, respectively, but not for the valence and the arousal ratings, $t(54) = 0.87$, $p = 0.386$, and $t(54) = 0.59$, $p = 0.559$, respectively. More specifically, for both the intensity and the

Fig. 1 Emojigrid used to measure valence (x-axis) and arousal (y-axis)

Fig. 2 Results of the experiment. The mean valence, arousal, intensity, and familiarity ratings as a function of the rating on the previous trial (either low or high). The error bars represent the standard error of the mean (SEM). The range of all rating scales is 0–100

familiarity ratings, we observed a positive serial dependence, indicating that the rating on a given trial was higher when the rating on the previous trial was high than when the rating on the previous trial was low.

Discussion

In this study, we investigated whether odor perception shows sequential effects. We analyzed data from a previous study in which participants consecutively rated 40 different odors on four different characteristics (intensity, familiarity, valence, and arousal). Inter-trial analyses on intensity and familiarity yielded a positive serial dependence for both ratings: the rating on the current trial was higher when the rating on the previous trial was high than when the rating on the previous trial was low. We observed no sequential effects for both the valence and arousal ratings. In summary, the olfactory system integrates previous stimuli into the current perception of odor intensity and familiarity (i.e., a positive sequential effect), while there is no sequential effect for valence and arousal.

As we already mentioned in the introduction, there are only few previous studies that investigated sequential effects for odor perception. The few studies that were done differed widely in the type of stimuli and experimental design. In the study arguably closest to ours, odors were presented in random sequences of six pleasant and six unpleasant odors in three different concentrations (Madigan et al. 1994). In this study, an absence of a sequential effect for valence in odor perception was also observed. Madigan and colleagues did not investigate arousal, intensity, and familiarity.

The absence of a sequential effect for affective odor ratings observed in the current study and the one by Madigan et al. (1994) is in contrast with reports on positive sequential effects for valence and arousal ratings for

viewing food images (Van der Burg et al. submitted). Positive sequential effects for intensity ratings have been reported within the auditory domain when participants were instructed to judge the loudness of a sound (Holland and Lockhead 1968; Jesteadt et al. 1977), while a negative sequential effect has been found for taste intensity (sweetness: Schifferstein and Frijters 1992). To the best of our knowledge, there are no studies investigating sequential affects for familiarity in any of the sensory modalities.

The positive sequential effect we found for intensity and familiarity in odor may be understood in the light of the neural olfactory processing. Different brain regions are engaged in processing olfactory stimuli depending on whether attention is being paid to their physical or affective qualities (Rolls et al. 2008). The amygdala plays an essential role in olfactory memory (Buchanan et al. 2003), integrating odor intensity and valence such that odors of more extreme (positive or negative) valence evoke significantly higher amygdala activity than more neutral odors (Winston et al. 2005). The behavioral and affective response to odors is to a large extent modulated by experience (Kadohisa 2013). By linking a negative valence to avoidance (danger) and a positive valence to approach behavior (reward; Root et al. 2014), the cortical amygdala mediates both innate and odor-driven behavioral responses. The positive sequential effects observed in this study for intensity and familiarity may reflect a lingering effect of the activation of the brain areas mediating their representation (Kiyonaga et al. 2017; Pascucci et al. 2019) to the degree that observers cannot perfectly separate active memory from an enhanced sense of familiarity (Makovski and Jiang 2008). An fMRI study on sequential odor effects would be of great interest.

The results of the current study may be relevant for marketers who are increasingly facilitating sampling opportunities for consumers to experience products like foods, beverages, and fragrances (Biswas et al. 2010). For instance, companies and retailers often provide free samples of food or beverage items in food courts and offer fragrance samples on scented strips in department stores or in magazines. When applying such sampling practices, marketers can account for a positive serial dependence for odor intensity that may affect the customers' preferences and choices. Also, the results may guide the design and use of olfactory-enhanced virtual and augmented reality systems for online shopping (Kim and Shin 2017; Petit et al. 2019) and communication (Xiang et al. 2016), gaming and training (Bordegoni and Carulli 2016; Chen et al. 2018), and tourism applications (Carulli et al. 2019; Guttentag 2010; Manghisi et al. 2017), in-car olfactory information displays (Bordegoni and Carulli 2016) and scent-based digital warning or messaging systems (Dobbelstein et al. 2017; Maggioni et al. 2018).

Limitations

The design of the current study was such that participants rated each odor on four different characteristics (valence, arousal, intensity, familiarity) in a single session. As a result, the inter-trial intervals were rather lengthy. Another possible design would be to distribute the experiment over four individual sessions or blocks and ask participants to rate each odor on a single characteristic in each block. Such a design could reduce the delay between two consecutive stimulus presentations and may therefore yield stronger serial effects. Furthermore, in the present study, the experimenter manually presented the odor stimuli to the participants, who took one or two sniffs following a verbal instruction. While our design more closely matches real-life conditions such as the marketing examples above, future studies could use olfactometer systems for the stimulus presentation to provide more precise control for stimulus steepness and timing.

Author Contribution AT, AMB, and JvE were involved in collecting the original dataset. EvdB performed the analyses and prepared the figures. AT and EvdB wrote the main manuscript text. All authors reviewed the final manuscript.

Data Availability The data generated during the current study will be made available online.

Declarations

Conflict of Interest The authors declare no conflict of interest.

Ethical Approval The study was carried out according to the guidelines of the Declaration of Helsinki on Biomedical Research Involving Human Subjects and approved by the local ethics committee (reference nr. 2019-024).

Informed Consent All subjects provided written informed consent.

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