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Wei-Lun Huang, Ming-Ru Tang, Chung-Hung Hong, and Si-Chen Lee

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Wei-Lun Huang,[1,a)] Ming-Ru Tang,[2,a)] Chung-Hung Hong,[2] and Si-Chen Lee[1,2,b)]

AFFILIATIONS

[1] Department of Electrical Engineering, Graduate Institute of Photonics and Optoelectronics, National Taiwan University, Taipei 10617, Taiwan

[2] Department of Electrical Engineering, Graduate Institute of Electronics Engineering, National Taiwan University, Taipei 10617, Taiwan

[a)] **Contributions:** Wei-Lun Huang and Ming-Ru Tang contributed equally to this work.
[b)] **Author to whom correspondence should be addressed. Electronic mail:** sclee@ntu.edu.tw.

ABSTRACT

The principle of olfactory perception had been widely studied. The core of the olfactory theory is based on two different mechanisms or the combination of the two. The first is the shape (weak shape) theory that the olfactory receptor only accepts the molecule with a complementary shape (lock to the key). The second is the vibrational theory that electrons on an odor molecule will be able to tunnel to the olfactory receptors quantum mechanically only when they are assisted by the specific bond vibrational energy of the molecules. Previous studies indicated that human subjects can distinguish the difference between the musk odorant molecules and its deuterated counterparts as evidence to advocate the theory. Scientists who refuted the vibration theory studied "musk-recognizing receptor", OR5AN1 and discovered that these receptors responded strongly and identically to the deuterated and normal musk odorants in the vitro environmental condition albeit they have different vibrational energies. In this paper, a new method is adopted to investigate the bond vibration-assisted olfactory theory. Narrow bandwidth infrared light sources with specific wavelengths were utilized to illuminate and excite molecular bond oscillation of the odorant molecules. By analyzing the experimental results of 23 human subjects. This study also supported the hypothesis of the "spin residual information theory" that the olfactory perception is aroused by the "residual spin information" of infrared photons left near the odor and receptor molecular bonding sites which absorbed or emitted the infrared photons.

The earliest widely known olfactory vibrational theory was proposed by Dyson in 1928[1] and further expanded by Robert Hamilton Wright in 1954.[2] The concept of the vibratory theory is that the oscillations (vibrations) of odor molecules which are characterized by particular chemical bonds have a special influence on olfactory receptors. This results in a characteristic pattern of electrochemical brain activity, interpreted as a specific odor. Quite different shapes of molecules may have similar odor. However, some molecules have mirror-like molecular bonds, such as D- and L-limonene, but the smells of them are totally different. It is obviously that the olfactory perception is not simply dependent only on the detection of vibrations of a particular molecular bond. Wright gave an explanation for this situation that olfactory receptors may have chiral structure as the odor molecules.[2] In 1996, Turin supported the Dyson's statement and made an inference: electrons on an odor molecule will tunnel quantum mechanically across a gap between two different energy levels to the olfactory receptors and assisted by bond vibrational energy of odorant molecules.[3–5] He speculated that the G-protein coupled receptors discovered by Linda Buck and Richard Axel actually measured molecular vibrations using inelastic electron tunneling, instead of molecular keys fitting molecular locks in shape.[3] In 2004, Vosshall and Keller refuted the vibration theory by publishing their experimental results and indicated that untrained human subjects cannot distinguish the odorant difference between the

normal acetophenone and its deuterated counterparts in the olfactory experiment by exchanging hydrogen and deuterium atoms in acetophenone.[6] In 2011, Turin et al. published a study showing the trained drosophila fruit flies can smell the difference between normal acetophenone and its deuterated (heavier) counterparts.[5] Two years later in 2013, they indicated that humans can distinguish the difference between normal musk molecules (cyclopentadecanone) from the deuterated ones with at least 14 carbon-deuterium bonds.[7] After two years, Eric Block et al. published a study refuted the plausibility of the vibrational theory of olfaction.[8] Their research results exhibit that the "musk-recognizing receptor" in human body, OR5AN1, which responded identically when presented with deuterated and non-deuterated musk odorants in the vitro environmental condition. They advocated that the argumentation of vibratory theory proposed by Turin does not apply to the situation of the human musk receptor OR5AN1 and the mouse thiol receptor MOR244-3. Scientists who supported and opposed the vibrational theory all raised and stand for their own arguments uninterruptedly during that period.

In this study, the narrow bandwidth infrared light sources were adopted to conduct olfactory experiments to investigate the plausibility of olfactory vibrational theory. The molecular bonds of odorant molecules can be excited to vibrate by absorbing the narrow bandwidth infrared light with specific wavelength. The smell of odorant molecules is expected to change during the infrared light illumination. The mechanism to generate human subjective consciousness (sight, hearing, taste, smell, and touch) is universally considered to be a process of the electrical neural pulse signals transmitted from the receptor to the brain. The hypothesis proposed in this study is that the electrical impulse transmission is only used for the computing processes in brain rather than generating the subjective phenomenal human olfactory sense.[9–14] The neural impulses act as a truck carrying a second signal "residual spin information" as a cargo through ascending neurons to the brain, the cargo but not the truck arouse the smell perception. The spin-residual information around the molecular could be further regarded as the information remained around the molecules by the absorption or generation of infrared photon. The photon spin would not disappear or be created immediately during the absorption or generation process and the information may stay or be balanced by an opposite spin residual around the chemical bond for some time. This mechanism was first mentioned in the related research by C. T. Kuo *et al*[15,16] to explain the discoveries of X-information that assisted the biochemical reaction of antibody and anti-gene through a thick blocking polymer wall. The X-information generated by the antibody (the spin residual information of the geometrical space-time structure of the antibody) can penetrate the polymer wall and induce biochemical reaction with anti-gene.

In addition, humans have approximately 400 functional genes coding for the olfactory receptors which have been derived from the Human Genome Project, but there are several tens of thousands different odor smell in ordinary people, so it could be inferred that the odor molecules may bind to a number of olfactory receptors, then the odor perception is determined by the combination of all signals from every receptor. Here we propose the "spin-residual information theory" to explain the olfactory perception which we believe is closer to the true mechanism. Fig. 1 shows the schematic diagram of the spin-residual information theory in the following equations:

$$\begin{pmatrix} A_1 \\ A_2 \end{pmatrix} + \begin{pmatrix} h\nu_1 \\ h\nu_2 \end{pmatrix} \xrightarrow{yields} \begin{pmatrix} A_1^* \\ A_2^* \end{pmatrix} + \begin{pmatrix} m_1 s_1 \\ m_2 s_2 \end{pmatrix} \tag{1}$$

$$\begin{pmatrix} A_1 \\ A_2 \end{pmatrix} + \begin{pmatrix} B_1 \\ B_2 \end{pmatrix} \xrightarrow{yields} \begin{pmatrix} B_1^* \\ B_2^* \end{pmatrix} \rightarrow \begin{pmatrix} B_1 \\ B_2 \end{pmatrix} + \begin{pmatrix} n_1 s_1' \\ n_2 s_2' \end{pmatrix} \tag{2}$$

$$\begin{pmatrix} S_1 \\ S_2 \end{pmatrix} = \begin{pmatrix} m_1 s_1 \\ m_2 s_2 \end{pmatrix} + \begin{pmatrix} n_1 s_1' \\ n_2 s_2' \end{pmatrix} \tag{3}$$

In the Eq. (1), the A_1 and A_2 represent the different chemical bonds of the odor molecules, the $h\nu_1$ and $h\nu_2$ represent the corresponding vibrational energy of the chemical bonds. When A_1 and A_2 absorbed the corresponding photons, they become excited and denoted by a superscript in star label, the spin of the photon will disappear immediately but the associated spin-residual information (space-time torsion structure) remained around A_1 and A_2, where s_1 and

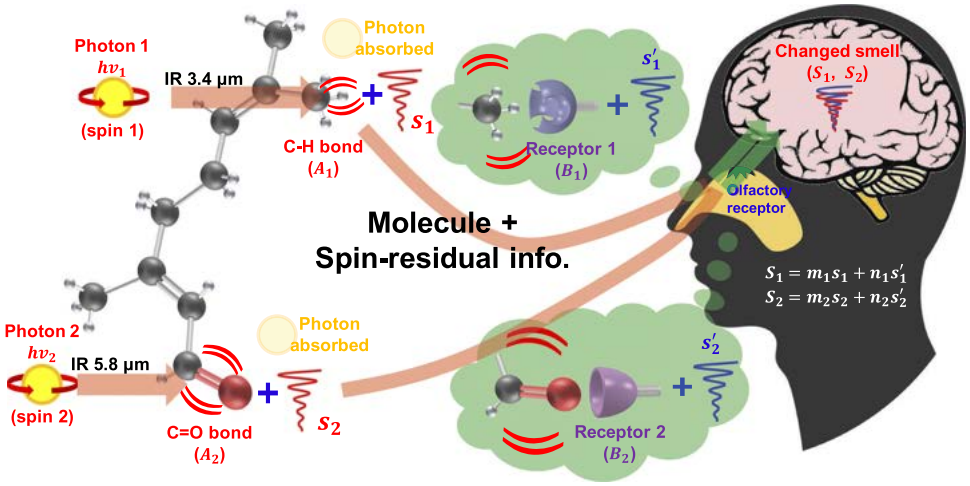

FIG. 1. The schematic diagram of the spin-residual information theory applied in the infrared excited odorant olfactory experiments.

s_2 are spin-residual information for A_1 and A_2, respectively, and the coefficient m_1 and m_2 are integers. They take sometimes to decay. When the odor molecules A_1 and A_2 bind to the corresponding receptors B_1 and B_2 as described in Eq. (2), the released energy will induce the receptor chemical bonds to vibrate as described in Eq. (2). After a while the vibration decays and emit infrared photons with a spin, in order to preserve space neutrality (an +1 spin creates an -1 opposite spin residual signal) that is the signal s_1' and s_2' for receptor 1 and 2, respectively, where n_1 and n_2 are integers. Macroscopically, the perception of the smell is the summation of the spin residual s_1 and s_2 from the excited odor molecular combined with the spin-residuals s_1' and s_2' of the receptor and the total spin-residual information were described as S_1 and S_2 in Eq. (3). The neural impulses act as a truck carrying a cargo S_1 and S_2 ascending to the central brain, the cargo arouse the phenomenal olfactory sense.

According to the previous report,[8] the measured electrical signal generated from the musk-recognizing receptors are identical when exposed to the deuterated and non-deuterated musk odorants. This is because that the human olfactory perception is determined not by the electrical signal transmitted from the olfactory receptor but by the accompanied spin-residual information which cannot be measured by electrical means.

The two odorants used in this study are citral and cyclopentadecanone. Absorption peaks of bonds vibration of these two odorants are located at medium infrared range, for citral and cyclopentadecanone, two main absorption peaks are both located at 3.4 μm and 5.8 μm, which are caused by the stretching vibration of the hydrocarbon bonds (C-H) and the bonding vibration of carbon-oxygen atoms (C=O), respectively.[17] To prepare the odor molecular samples, ethanol is used as a solvent to dilute the odor molecules to weight percent concentration (wt%) which is suitable for human olfaction. In order to ensure that the variations of odor intensities could be clearly distinguished by human subjects, the citral and cyclopentadecanone was diluted to 0.05 and 0.5 wt%, respectively. In our olfactory experiment, these two different molecular bonds were excited by illuminating the odorant molecules with narrow bandwidth infrared light sources at the corresponding wavelength. The adopted infrared light source which is based on a waveguide resonant thermal emitter with narrow bandwidth characteristic was developed by our research group.[17–20] Fig. 2(a) displays two thermal radiation spectra of two independent infrared light sources. The blue and red curves represent the radiation spectra of the waveguide thermal emitter heated at a working temperature of 210°C with emission peak wavelengths at 3.4 and 5.8 μm, respectively. The ratio of FWHM to the peak wavelength are 0.047 and 0.022 for the emission wavelength at 3.4 and 5.8 μm, respectively. The radiation power is about 15-20 mW/cm^2 with the illuminating area of 1 cm^2.

The experimental arrangement must be prepared in advance before the formal olfactory experiment start. The 50 μl odor solution was dropped in central circle, by a micropipette, into the center area of a 90 mm diameter filter paper with 10 pinholes in the central circular area, as shown in Fig. 2(b). The size and locations of pinholes are identical for each measurement. After standing for 3 minutes, waiting for the ethanol solvent to evaporate, then the experimental preparation of the odor reagent is completed. The purpose of the stamped holes is to allow the odor molecules, which is

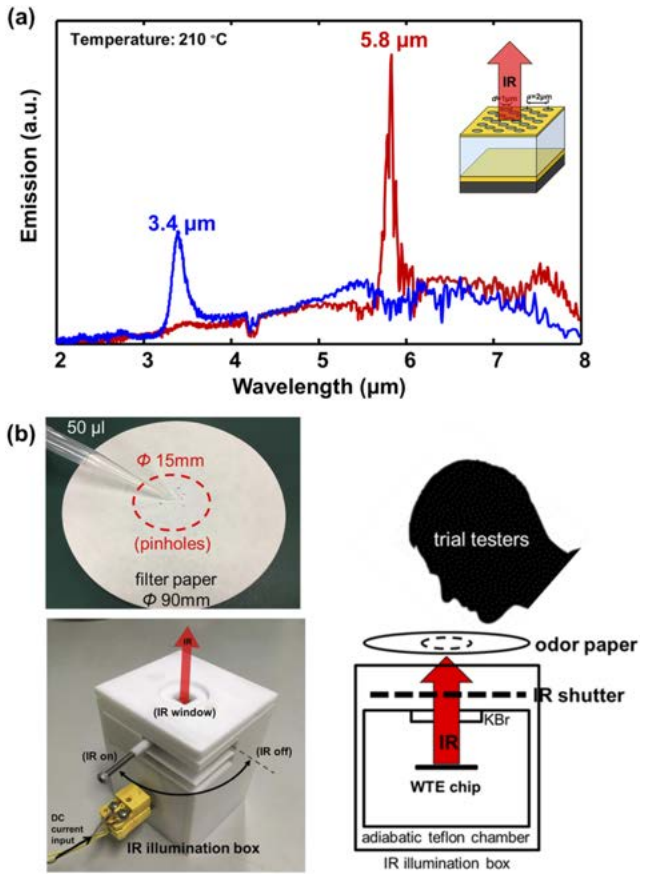

FIG. 2. (a) The thermal radiation spectra of the adopted infrared light sources with emission wavelength equal 3.4 and 5.8 μm. (b) The experimental arrangement.

illuminated by infrared light, to pass through the filter paper and reach the nasal cavity of the trial tester. To eliminate the concern about thermal effect, the waveguide thermal emitter is isolated in an adiabatic TEFLON chamber. The distance between IR emitter and odor reagent is kept in 7 cm during experiments. In addition, thermocouple was used to record the temperature of the filter paper. The temperature was fond to stay at room temperature during the odor experiments. 23 persons were invited to the odor experiments. For each human subject, there are six different types of odorant experiment consist of two odor molecules (citral and cyclopentadecanone) illuminated by three different wavelengths (3.4 μm, 5.8 μm, and pseudo IR) of infrared light. This experiment is a single-blind study; human subject does not know what kind of infrared light source is being used to illuminate odorant molecules during the experiment. The sequence of different types of infrared light illuminating experiments is in a random arrangement chosen by an independent assistant. In order to exclude the psychological factors anticipated by human subjects, the third type of infrared illumination condition is adopted as a control, which is the pseudo IR. In fact, it represents the situation that there is no infrared emitter in the chamber and thus no illumination. All subjects were required to practice for deep

breathing proficiently at least 10 minutes before the formal olfactory experiments start so as to ensure every subject can carefully discern the subtle odor variations in each breath. Then it is assumed that, each inhale and exhale are periodically and quantitatively in the individual case. Each subject was asked take a deep breath inhale and then exhale for ten times uninterruptedly in each experiment. The odor molecules were not illuminated by infrared light during the first five times of deep breaths. Because the intensities of the smell sensed by humans will decrease with the number of times of smelling, the purpose of the first five times of deep breaths before IR illumination is to stabilize the smells intensities sensed by human subjects. After the fifth deep breath, the experimental assistant will open the IR shutter immediately to start the infrared light illumination on odorant molecules from the sixth to the tenth deep breath. Human subjects have to record the smells intensities sensed by themselves, which are described as numerical integer in every deep breath. A reference value for smell intensity is established between every human subject, the smell intensity value felt at the 5th breathing (just before IR shutter is opened) is defined to be 10. If the smell intensity felt is stronger than of the 5th breathing, the intensity value is expressed as 10 plus one, for instance, +11. If subject is positively aware that the smell intensity is significantly stronger, the intensity value is expressed as more than 2, i.e. ≧12. In contrast, the intensity value is lower than 10 if subject felt the smell is weaker, for instance, +9. If the smell is significantly weaker, the intensity value is expressed as more than 2, i.e. ≦8. The experimental procedure is described as follows. (1) Before the formal experiment start, each human subject has to practice for deep breathing proficiently at least 10 minutes. (2) A human subject will take a total of ten deep breaths inhale and exhale in each experiment, and carefully feel the odorant intensity they experienced. (3) The experimental assistant will immediately open the IR shutter as the human subject completes the first five deep breaths, and then the human subject follows the sixth to tenth deep breath uninterruptedly. (4) The human subject recorded the odorant value smelled by each deep breath on a pre-prepared form with intensity scale table and then took a rests for ten minutes before proceeding to the next olfactory experiment.

Fig. 3 and Fig. 4 display the raw data of the odorant intensity value recorded by 23 subjects, which were represented by 23 different color curves in each figure, for odor molecule citral and cyclopentadecanone, respectively. The horizontal axis is the breathing sequence of human subject, and the vertical axis is the smelled odorant intensity value. The area marked with a pink background in the chart represents the part that is illuminated by infrared light. No matter what odor molecules, i.e. citral or cyclopentadecanone, were chosen, it is obvious for most of the subjects that the initial odorant intensity values were higher in the first few deep breaths (about 1st – 3rd), and then stabilized in the 4th – 5th deep breath. It can be inferred that the sense of smell is similar to that of pain, that is, human olfaction has adaptive characteristics.

In order to exclude the influence of human adaptive characteristics and the psychological factors, in the following data analyses, the experimental results with IR illumination will be normalized to the case of pseudo IR. The normalized method is described as follows. In each person and each sequence of breath, the normalized data equals to the smell intensity values recorded in the IR illumination experiments (IR 3.4 μm and 5.8 μm) subtracted from recorded

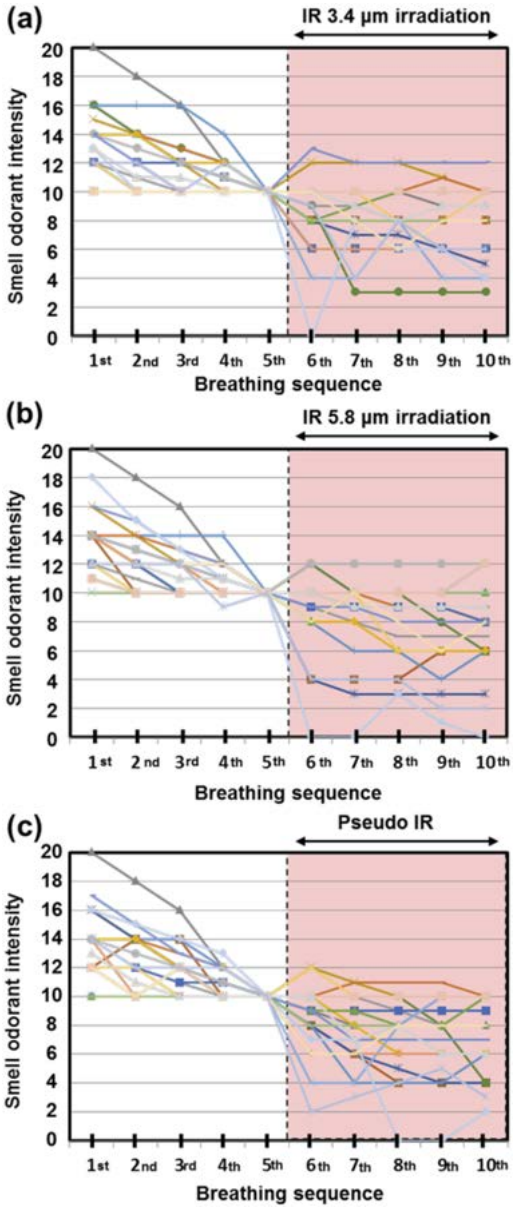

FIG. 3. The raw data of citral olfactory experiments recorded by 23 human subjects. The variations of smell odorant intensity-breathing sequence in infrared illuminating experiments with wavelength of (a) 3.4 μm, (b) 5.8 μm, and (c) pseudo IR.

values in the case of pseudo IR.

$$Normalized\ intensity \equiv IR\ illumination^{nth\ breathing} - Pseudo\ IR^{nth\ breathing}$$

Noticeable that, the pseudo IR means no infrared irradiation from KBr window. Since the variation of odorant intensity felt by human subjects is dynamic whether it is before or after IR illumination.

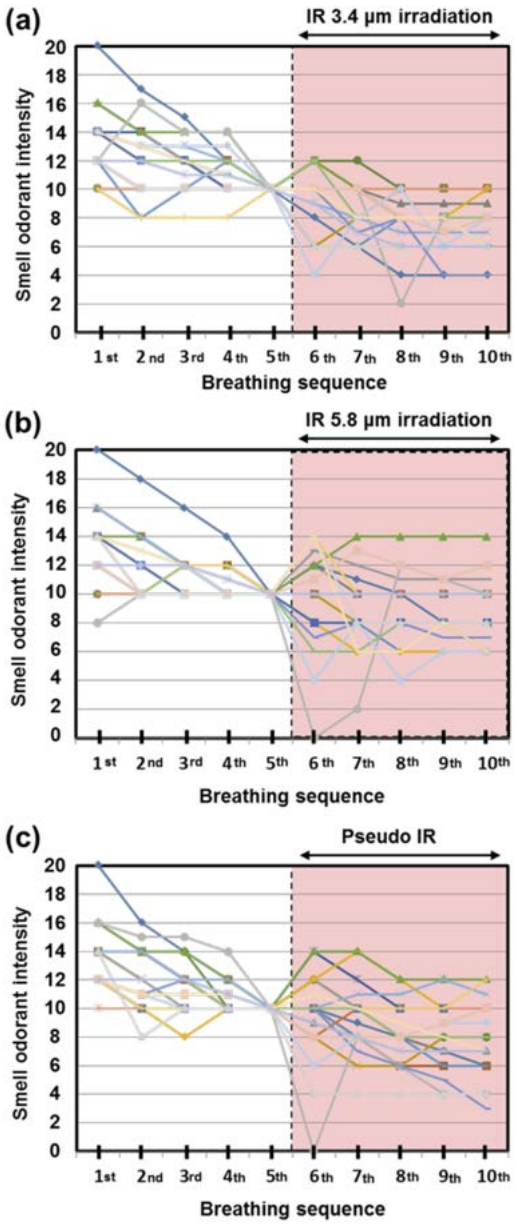

FIG. 4. The raw data of cyclopentadecanone olfactory experiments recorded by 23 human subjects. The variations of smell odorant intensity-breathing sequence in infrared illuminating experiments with wavelength of (a) 3.4 μm, (b) 5.8 μm, and (c) pseudo IR.

In order to analyze the dynamic behavior of the variation between the changed odorant intensities and the number of human subjects, the classification of human subjects in the raw data was defined according to the following definition.

Stronger: smell intensity change ≧ +2
Unchanged: -2 < smell intensity change < +2
Weaker: smell intensity change ≦ -2

The normalized experimental results of odorant molecules citral and cyclopentadecanone are displayed in Fig. 5 and Fig. 6, respectively. The horizontal axis is the deep breathing sequence of human subject, and the vertical axis is the corresponding number of subjects. The red, blue, and green curves in each chart represent three different categories of the smell intensity felt by subjects which are stronger, unchanged, and weaker, respectively. The C-H bonds in citral were excited to stretch after 3.4 μm IR illumination, and the corresponding statistics results is shown in Fig. 5(a). In the 6th to 7th breathing, about 65% of human subjects felt that the smell intensity was unchanged; however, the number of subjects who felt that the smell intensity was getting stronger is gradually increasing. At the 8th breathing, the number of human subjects felt the stronger smell is 10% more than that in the unchanged ones and much more than the weaker ones. At this time, the number of subjects represented by both the blue and red curves accounts for about 80% of the total. At the 9th to 10th breathing, the number of subjects represented by the red curve then dropped to 22%, and that of the blue curve rose back to 65%. As for the number of subjects who felt that the smell intensity is weaker (green curve) is maintain about

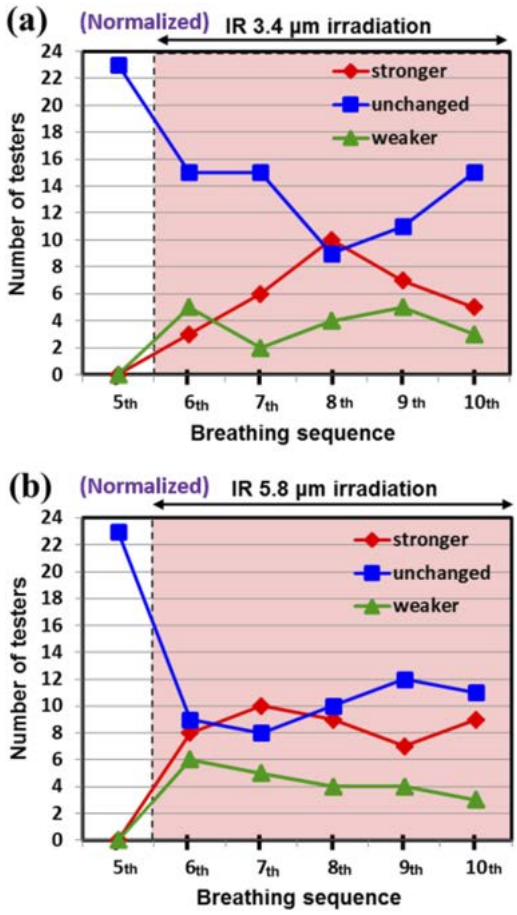

FIG. 5. Normalized statistics of human subjects in olfactory experiments of odorant molecule citral with infrared illumination at wavelength (a) 3.4 μm and (b) 5.8 μm.

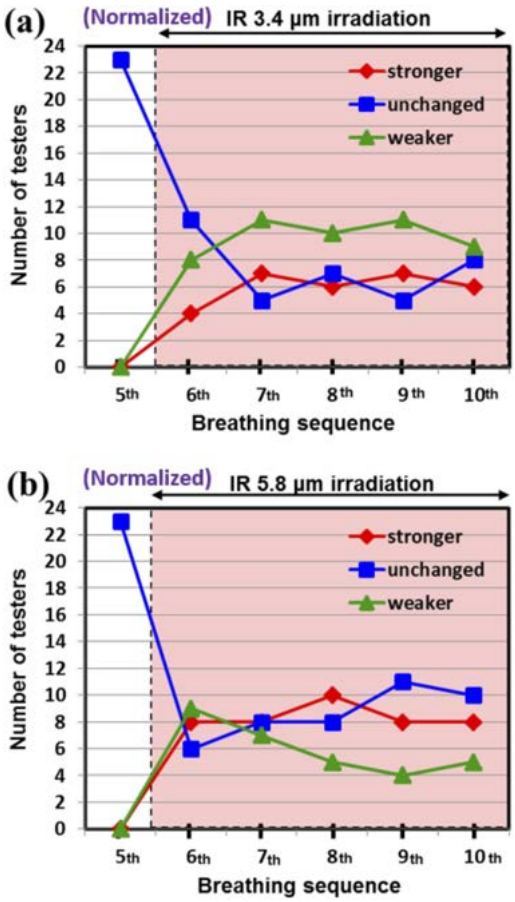

FIG. 6. Normalized statistics of human subjects in olfactory experiments of odorant molecule cyclopentadecanone with infrared illumination at wavelength (a) 3.4 μm and (b) 5.8 μm.

20% or less of the total human subjects. From the above statistical results, it can be inferred that, although a parts of human subjects felt the smell intensity is unchanged, in the 8th breathing, the influence of the IR excited C-H bonding stretch in citral still affects results in a considerable number of subjects, the smell intensity become stronger.

The molecular C=O bond in citral is excited by 5.8 μm IR illumination, and the corresponding statistics results are shown in Fig. 5(b). It is obvious that the experimental result of 5.8 μm IR illumination is very different from that of the 3.4 μm IR illuminations. In the 6th to 8th breathing, the number of human subjects who felt the smell intensity is strong is very close to that of unchanged (about 35 – 45% of the total subjects respectively). The results of the 9th to 10th breaths are similar to that in Fig. 5(a), the number of subjects represented in blue curve (unchanged) in greater than that of the red curve (stronger), but the difference is only about 8 – 13%. As for the number of human subjects represented in green curve (weaker) in about 26% or less of the total subjects. From the above experimental statistic result displayed in Fig. 5(a) and Fig. 5(b), it can be inferred that the smell intensities of the odorant molecule citral will be affected by its own molecular bonding vibrations, which is excited by the external infrared illumination. It is obviously that whether it is IR 3.4 μm or 5.8 μm illuminations, the number of human subjects who felt smell stronger is significantly more than those who felt weaker after the 7th breathing. This result indicates that the effect of the molecular bonding vibration excited by infrared illumination is not immediately active to human olfaction. This phenomenon of non-immediate response is also quite consistent with the spin residual information theory. Overall, the infrared light sources with two different wavelengths to excite citral are effective to increase the smell intensity by a considerable number of the human subjects.

Fig. 6(a) and Fig. 6(b) display the normalized statistic data of the olfactory experiment of odorant molecule cyclopentadecanone which is illuminated by infrared light with wavelength 3.4 μm and 5.8μm, respectively. The experimental results of cyclopentadecanone with IR 3.4 μm illumination are very different from that of citral. At the 7th to 10th breathing, the number of human subjects who felt the weaker smell (green curve) rised to 40 – 49%, and who felt the stronger smell (red curve) also rised to 35 – 40% of all subjects, as shown in Fig. 6(a). In contrast, the number of subjects who felt the unchanged smell (blue curve) drops to 22 – 35% at the 7th to 10th breathing. This result is exactly the opposite to that of the citral. In Fig. 6(b) with 5.8 μm illumination, at the beginning of IR illumination (at the 6th breathing), the number of subjects represented by the green curve (weaker) rised to 40% of all subjects, and then dropped to 22% at the 10th breathing. The number of subjects represented in red (stronger) and blue (unchanged) accounts to about 35 – 48% at the 7th to 10th breathing. In the IR 5.8 μm illuminated olfactory experiment, in the 10th breathing, the statistic result of cyclopentadecanone is very similar to that of the citral displayed in Fig. 5(b). The C=O bond connected on the giant benzene ring of the odorant molecules such as cyclopentadecanone, is known in the vibration theory as the main cause which generate the musk flavor. This is the reason why the number of human subjects who smell weaker dropped to 22% at 8 – 10th breathing. Since all of the C-H bonds (a total of 28 C-H bonds) on the giant benzene ring in a cyclopentadecanone molecule were excited to stretching vibration by 3.4 μm infrared illumination, such a lots of bonding vibration around the molecular main part may affects the olfactory receptor to detect the C=O bond, and then results in a considerable number of human subjects who felt that the smell intensity becomes weaker during 3.4 μm IR illuminating. Overall, in the olfactory experiment of the citral illuminated by infrared light (whether IR 3.4 μm or 5.8μm), after the 7th breathing, only a few tests felt that the smell became weaker (less than 22%), and human subjects who felt that the smell became stronger or unchanged accounted for 80% of the total number. In the olfactory experiment of the cyclopentadecanon illuminated by 5.8 μm of infrared light, after the 8th breathing, less than 22% of the subjects felt that the smell was weaker, and the subjects who felt that the smell became stronger or unchanged exceeded 75% of the total number. Whether it is the citral or the cyclopentadecanon of infrared light illuminating experiments, it can be found that the odor change effects caused by infrared light is not immediate. The excitation of infrared light illumination can be regarded as a kind of spin information residual near the photon absorption sites of odor molecular bonding vibrations.[9–14] human olfactory theory

is not completely independent of odor molecular bonding vibrations. In this study, by analyzing the olfactory experimental results, the molecular bond vibration excited by infrared light illumination does affect the smell variations that people experienced. Different wavelengths of narrow bandwidth infrared light will excite different bonding vibrations in the odorant molecules and cause different effects on the smell variations.

Narrow bandwidth infrared light sources were adopted in the application of olfactory experiments. The C-H and C=O molecular bonds in the odorant molecules such as citral and cyclopentadecanone are excited to vibrate by absorbing the infrared light illumination with wavelengths of 3.4 μm and 5.8 μm, respectively. The statistical data exhibits that the IR 3.4 μm and 5.8 μm illumination results in a considerable number of human subjects (about 43%) who felt that the smell intensity becomes stronger when IR illuminating. In the olfactory experiment of cyclopentadecanone, about 43% of the human subjects think that the smell intensity is stronger when the odorant molecules were exposed to 5.8 μm infrared light. The bonding vibration of a large number of C-H bonds, which were excited by 3.4 μm infrared light, on the main body of the odor molecule interfered the function of C=O bonds which dominates the musk flavor, and then caused about 48% human subjects who felt that the smell intensity is weaker when IR illumination. By analyzing the olfactory experimental results of 23 human subjects, the excited molecular bond vibration does affect the smell variations felt by the non-negligible number of subjects. The experimental results of this study exhibits the great credibility of spin-residual information theory in the generating mechanism of human consciousness.

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REFERENCES

[1] G. Dyson, Perfumery and Essential Oil Record **19**, 456–459 (1928).
[2] R. H. Wright, Journal of Applied Chemistry **4**(11), 611–615 (2007).
[3] L. Turin, Chemical Senses **21**(6), 773–791 (1996).
[4] L. Turin, *The secret of scent: Adventures in perfume and the science of smell* (Faber & Faber, 2006).
[5] M. I. Franco, L. Turin, A. Mershin, and E. M. Skoulakis, Proceedings of the National Academy of Sciences 201012293 (2011).
[6] A. Keller and L. B. Vosshall, Nature Neuroscience **7**(4), 337 (2004).
[7] S. Gane, D. Georganakis, K. Maniati, M. Vamvakias, N. Ragoussis, E. M. Skoulakis, and L. Turin, PloS One **8**(1), e55780 (2013).
[8] E. Block, S. Jang, H. Matsunami, S. Sekharan, B. Dethier, M. Z. Ertem, S. Gundala, Y. Pan, S. Li, and Z. Li, Proceedings of the National Academy of Sciences 201503054 (2015).
[9] S. C. Lee, Buddhism and Science **16**(2), 73–80 (2015).
[10] D. J. Chalmers, *The conscious mind: In search of a fundamental theory* (Oxford University Press, 1996).
[11] T. Nagel, Philosophy **73**(3), 337–352 (1998).
[12] M. Stein, *Jung's map of the soul: An introduction* (Open Court Publishing, 1998).
[13] S. Hameroff, NeuroQuantology **5**(1) (2007).
[14] S. R. Hameroff and R. Penrose, Journal of Consciousness Studies **3**(1), 36–53 (1996).
[15] C. T. Kuo, F. T. Chuang, P. Y. Wu, Y. C. Lin, H. K. Liu, G. S. Huang, T. C. Tsai, C. Y. Chi, A. M. Wo, H. Lee, and S. C. Lee, Journal of Applied Physics **116**, 044702 (2014).
[16] C. T. Kuo, C. Y. Chi, P. Y. Wu, F. T. Chuang, Y. C. Lin, H. K. Liu, G. S. Huang, T. C. Tsai, A. M. Wo, H. Lee, and S. C. Lee, Journal of Applied Physics **119**, 024702 (2016).
[17] C. C. Wang, L. Davis, Jr., C. Wu, S. Japar, H. Niki, and B. Weinstock, Science **189**, 797–800 (1975).
[18] Y. T. Wu, Y. T. Chang, H. H. Chen, H. F. Huang, D. C. Tzuang, Y. W. Jiang, P. E. Chang, and S. C. Lee, IEEE Photonics Technology Letters **22**(15), 1159–1161 (2010).
[19] Y. W. Jiang, Y. T. Wu, M. W. Tsai, P. E. Chang, D. C. Tzuang, Y. H. Ye, and S. C. Lee, Optics Letters **34**(20), 3089–3091 (2009).
[20] H. H. Chen, Y. W. Jiang, Y. T. Wu, P. E. Chang, Y. T. Chang, H. F. Huang, and S. C. Lee, Applied Physics Letters **97**(16), 163112 (2010).