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REVIEW ARTICLE

Physiological effects of wood on humans: a review

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Abstract It is empirically known that wood can cause a comfort enhancement effect in humans. On the other hand, not enough scientific knowledge based on evidence-based research is available on this subject. However, data using physiological indices have increasingly accumulated in recent years. This review provides an overview of the current situation for peer-reviewed reports related to the physiological effects of wood. We reviewed reports that elucidated the effects of wood-derived stimulations on the olfactory, visual, auditory, and tactile sensations using physiological indices such as brain activity (e.g., near-infrared spectroscopy) and autonomic nervous activity (e.g., heart rate variability and blood pressure). It became clear that many studies were limited by (1) a small number of participants, mostly aged in their 20s; (2) use of only a single stimulus (e.g., only olfactory or only visual), or (3) an incomplete experimental design. In addition, this review examined the field of forest therapy, for which there is abundant research. Further study is needed to elucidate the physiological effects of wood on humans.

Keywords Wood · Human · Physiological effect · Brain activity · Autonomic nervous activity

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Introduction

In the 7 million years that human species have existed, over 99.99% of our evolution has taken place in a natural environment. Even since the beginning of urbanization with the industrial revolution, less than 0.01% of our species' time has been spent in an artificial and urbanized environment. It is considered that the human body is adapted to a natural setting [1, 2]. We proceeded with this research based on the hypothesis that highly urbanized and artificial environments cause a state of physiological stress, which manifests as an increase in sympathetic nervous activity, blood pressure, heart rate, and stress hormone. Indeed, over recent decades, there have been reactions to the urbanized environment, suggesting a possible second phase in how we interact with it. For example, the Japanese term "Shinrin-yoku" [3], which means "taking in the forest atmosphere through all of our senses", was proposed in 1982 by a Forestry Agency secretary in Japan and in 1984, an American clinical psychologist coined the term "Technostress" [4]. Nature therapy, including relaxation by exposure to natural stimuli from forests, urban parks, flowers, and natural wooden materials, is receiving increasing attention, and scientific data in support of this have begun to accumulate in various research fields [5].

In particular, there have been many reports related to forest therapy experiments, for example, these have investigated reduction of prefrontal cortex activity [6], enhancement of parasympathetic nervous activity [7–18], inhibition of sympathetic nervous activity [7–11, 14–18], reduction of blood pressure [8–11, 16, 19], reduction of pulse rate [7–10, 19], and reduction in the concentrations of stress hormone (e.g., cortisol) [7–11, 19]. Those results demonstrate the relaxation effects of forest therapy.

With respect to wooden material therapy, the original article about the physiological effects of olfactory stimulation response was published in 1992 [20, 21]. However, since then the amount of data collected according to the principles of evidence-based medicine [22] is extremely limited. Early studies on wooden material therapy investigated the effects of temperature and humidity [23–26]. These were followed by studies on the effects of stimuli on the senses using subjective evaluation indexes [27–32]. More recently, experiments based on physiological response indexes have been conducted.

In this review, our aim was to summarize the peer-reviewed papers that have accumulated since 1992, the year in which the first article on this research area was published, which describe the physiological effects of wood-derived stimuli on humans via the main senses. We also discuss individual differences research, which has recently become an important subject.

Physiological effects of wood on humans

Early investigations on wooden material therapy tended to use only a single indication, such as blood pressure. Recently, it has become more common to make simultaneous measurements of multiple physiological indicators. An example of the experimental apparatus and setup for an olfactory stimulation experiment is shown in Fig. 1.

Common physiological evaluations include (1) brain activity, (2) autonomic nervous activity, (3) endocrine activity, and (4) immune system activity [33]. Until recently, the most commonly used indicator of brain activity was electroencephalography (EEG), but the mainstream of recent research has been to measure oxygenated hemoglobin (oxy-Hb) concentration in the prefrontal cortex using near-infrared spectroscopy (NIRS). Initial indicators of autonomic nervous activity included blood pressure, heart rate, pupil diameter, and pupillary light reflex, but it is more common now to measure heart rate variability (HRV), which can be separated into evaluations of sympathetic nervous activity and parasympathetic nervous activity. For an endocrine index, the improvement of analytical techniques has enabled the measurement of stress hormones contained in saliva, such as cortisol concentration. Natural killer cell activity is often used as an indicator of immune activity. The physiological indices used to evaluate the physiological effects of wood are discussed further in reviews by Burnard and Kutnar [34] and Tsunetsugu et al. [35].

The present review summarizes the scientific literature on this subject published over the last 25 years (Table 1). There were three inclusion criteria for the studies: (1) publication in the English or Japanese language; (2) publication between January 1992 and August 2016, and (3) only human studies were included. The search for relevant papers was conducted using the PubMed and CiNii databases. We performed separate searches using keyword combinations of terms related to wood and terms related to physiological effects. The terms related to wood or wood-derived components were as follows: "wood", "wood material", "natural wooden material", "Japanese cypress", "Japanese cedar", "hinoki", "sugi", "hiba", "α-pinene", "limonene", and "cedrol". The terms related to physiological effects were the following: "brain activity", "autonomic nervous activity", "endocrine activity", "immune activity", "physiological effects", and "physiological relaxation". This search identified 635 references. Other publications cited in the collected papers were then examined and added to our list if relevant. After applying our three inclusion criteria, we retained 41 articles for our review. Here, we have introduced and summarized this literature according to the sensory mode stimulated: olfactory, visual, auditory, and tactile.

Olfactory stimulation

Conventionally, experience suggests that the smell of wood has a relaxing effect. However, data on the physiological

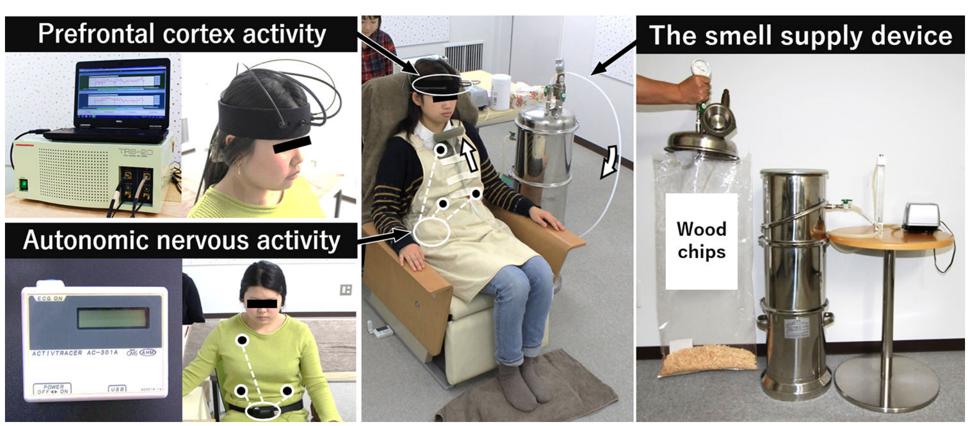

Fig. 1 An example of olfactory stimulation apparatus and setup

Table 1 Overview of research on wooden material therapy

Year	Authors	Sense	Physiological indices	Summary	Stimulation/control (stimulation time)		Participants	Article type	Ref Nos.
2016	Ikei et al.	Olfaction	Autonomic nervous activity	Enhancement of parasympathetic nervous activity (measured using HRV) Decrease in heart rate *Comparison with control	α-Pinene/air	(90 s)	Female univ. students $n = 13$	Short communication	[46]
2016	Song et al.	Olfaction	Immune activity (Ref No. [37])	Increase in natural killer cell activity †Comparison with pre-stimulation	Japanese cypress wood oil	(3 nights)	Adult male $n = 12$	Review	[5]
			Brain activity (Ref No. [54])	Decrease in oxy-Hb concentration in the right prefrontal cortex *Comparison with control	Japanese cypress leaf oil/air	(90 s)	Female univ. students $n = 13$		
			Autonomic nervous activity (Ref No. [54])	Enhancement of parasympathetic nervous activity *Comparison with control					
			Brain activity (Ref No. [38])	Calming effect on the prefrontal cortex activity †Comparison with pre-stimulation	Japanese cedar chips	(90 s)	–		
			Autonomic nervous activity (Ref No. [38])	Decrease in systolic blood pressure †Comparison with pre-stimulation					
			Autonomic nervous activity (Ref No. [39])	Performed arithmetic tasks Salivary chromogranin A Increase: cedar wall panels No change: no cedar wall panels †Comparison with pre-stimulation	Japanese cedar interior wall panels/no Japanese cedar interior wall panels	(45 min)	Male univ. students $n = 16$		
			Brain activity (Ref No. [55])	After performance of a sustained task on a VDT Decrease in alpha band power Increase in theta band power *Comparison with control	Siberian fir leaf oil/air	(40 min)	Male univ. students $n = 9$		
			Autonomic nervous activity (Ref No. [55])	After performance of a sustained task on a VDT Decrease in pulse rate *Comparison with control					
			Brain activity (Ref No. [41])	Increase in the amplitude of the early and late CNV components *Comparison with control	Hiba oil/air	(30 min)	Females of twenties $n = 16$		
			Autonomic nervous activity (Ref No. [38])	Decrease in systolic blood pressure †Comparison with pre-stimulation	α-Pinene and limonene	(90 s)	–		
			Autonomic nervous activity (Ref No. [45])	Enhancement of parasympathetic nervous activity (measured using HRV) Decrease in heart rate *Comparison with control	D-Limonene/air	–	–		

Table 1 continued

Year	Authors	Sense	Physiological indices	Summary	Stimulation/control (stimulation time)		Participants	Article type	Ref Nos.
			Brain activity (Ref No. [44])	Calming effect on the left and right prefrontal cortices *Comparison with control	Japanese cypress chips made by air drying/Japanese cypress chips made by high-temperature drying	–	Female univ. students $n = 19$		
		Vision	Autonomic nervous activity (Ref Nos. [62–64])	Plus rate increase: 45% wood; decrease: 30% wood Diastolic blood pressure Decrease: 30% †Comparison with pre-stimulation	Actual rooms (13 m^2) (30 and 45% wood)	(90 s)	–		
			Autonomic nervous activity (Ref No. [61])	Systolic blood pressure Evaluated the Japanese wall panels "like" group: decrease "dislike" group: no change Evaluated the white steel wall panels "Dislike" group: increase †Comparison with pre-stimulation	Full-sized Japanese cypress wall panels/white steel wall panels	(90 s)	Male univ. students $n = 14$		
		Taction	Autonomic nervous activity (Ref No. [74])	Systolic blood pressure and pulse rate Small fluctuation: Japanese cypress and cedar Large fluctuation: stainless steel	Japanese cypress, Japanese cedar, and stainless steel board	–	–		
			Autonomic nervous activity (Ref No. [75])	Systolic blood pressure Increase: aluminum, acrylic plastic, and cold acrylic plastic board No change: worm aluminum, cedar, cypress, and oak board Decrease: cold oak board †Comparison with pre-stimulation	Japanese cypress, Japanese cedar, oak, acrylic plastic, and aluminum (cooling, room temperature, and warming)	–	–		
2015	Ikei et al.	Olfaction	Brain activity	Decrease in oxy-Hb concentration in the right and left prefrontal cortex (measured using TRS) *Comparison with control	Japanese cypress chips made by air drying/high-temperature drying	(90 s)	Female univ. students $n = 19$	Short communication	[44]
2015	Ikei et al.	Olfaction	Brain activity	Decrease in oxy-Hb concentration in the right prefrontal cortex (measured using TRS) *Comparison with control	Japanese cypress leaf oil/air	(90 s)	Female univ. students $n = 13$	Original article	[54]
			Autonomic nervous activity	Enhancement of parasympathetic nervous activity (measured using HRV) *Comparison with control					

Table 1 continued

Year	Authors	Sense	Physiological indices	Summary	Stimulation/control (stimulation time)	Participants	Article type	Ref Nos.
2015	Miyazaki et al.	Olfaction	Autonomic nervous activity (Ref No. [38])	Decrease in systolic blood pressure †Comparison with pre-stimulation	α-Pinene and limonene (90 s)	–	Review (in Japanese with English abstract)	[60]
			Autonomic nervous activity (Ref No. [45])	Enhancement of parasympathetic nervous activity (measured using HRV) Decrease in heart rate *Comparison with control	D-Limonene/air –	–		
		Vision	Autonomic nervous activity (Ref Nos. [62–64])	Plus rate increase: 45% wood; decrease: 30% wood Diastolic blood pressure Decrease: 30% wood †Comparison with pre-stimulation	Actual rooms (13 m^2) (30 and 45% wood) –	–		
		Taction	Autonomic nervous activity (Ref No. [74])	Systolic blood pressure and pulse rate Small fluctuation: Japanese cypress and cedar Large fluctuation: stainless steel	Japanese cypress, Japanese cedar, and stainless steel board			
			Autonomic nervous activity (Ref No. [75])	Blood pressure Increase: warmed aluminum No change: cold cypress, cedar, and oak †Comparison with pre-stimulation	Cold oak, Japanese cedar, Japanese cypress, and warmed aluminum –	–		
2015	Burnard and Kutnar	Vision	Autonomic nervous activity (Ref No. [62])	Decrease in pulse rate *Comparison with designed wooden room	Standard wooden room/designed wooden room (90 s)	–	Review	[34]
			Autonomic nervous activity (Ref No. [61])	Systolic blood pressure Evaluated the Japanese wall panels "Like" group: decrease "Dislike" group: no change Evaluated the white steel wall panels "Dislike" group: increase †Comparison with pre-stimulation	Full-sized Japanese cypress wall panels/white steel wall panels (90 s)	–		
			Brain activity (Ref No. [64])	Total-Hb concentration in the prefrontal cortex (measured using NIRS) Increase: 0 and 90% wood No change: 45% wood †Comparison with pre-stimulation	Actual rooms (13 m^2) (0, 45, and 90% wood) (90 s)	–		

Table 1 continued

Year	Authors	Sense	Physiological indices	Summary	Stimulation/control (stimulation time)	Participants	Article type	Ref Nos.
			Autonomic nervous activity (Ref No. [64])	Plus rate Increase: 45% wood No change: 0 and 90% wood Systolic blood pressure Decrease: 90% wood No change: 0 and 45% wood Diastolic blood pressure Decrease: 0, 45, and 90% wood †Comparison with pre-stimulation				
2014	Joung et al.	Olfaction	Autonomic nervous activity	Enhancement of parasympathetic nervous activity (measured using HRV) Decrease in heart rate *Comparison with control	D-Limonene/air (90 s)	Female univ. students $n = 13$	Original article	[45]
2014	Matsubara and Kawai	Olfaction	Autonomic nervous activity	Performed arithmetic tasks (U-K test) Salivary chromogranin A Increase: cedar wall panels No change: no cedar wall panels †Comparison with pre-stimulation	Japanese cedar interior wall panels/no Japanese cedar interior wall panels (45 min)	Male univ. students $n = 16$	Original article	[39]
2012	Hori et al.	Inhalation (lower airway)	Brain activity	Increase in rCBF in the right and left hippocampus (measured using SPET) †Comparison with pre-stimulation	Cedrol (10 min)	Totally laryngectomized male participants $n = 11$	Short communication	[53]
2012	Tsunetsugu et al.	Vision	Autonomic nervous activity (Ref Nos. [62–64])	Plus rate Increase: 45% wood; decrease: 30% wood Systolic blood pressure Decrease: 90% wood Diastolic blood pressure Decrease: 30 and 90% wood †Comparison with pre-stimulation	Actual rooms (13 m^2) (30, 45, and 90% wood) –	–	Book	[38]
		Olfaction	Brain activity	Decrease in Total-Hb concentration in the right and left prefrontal cortex (measured using NIRS) †Comparison with pre-stimulation	Japanese cedar chips (90 s)	–		
			Autonomic nervous activity	Decrease in systolic blood pressure †Comparison with pre-stimulation				
			Brain activity (Ref No. [41])	Increase in the amplitude of the early and late CNV components *Comparison with control	Hiba oil/air –	–		

Table 1 continued

Year	Authors	Sense	Physiological indices	Summary	Stimulation/control (stimulation time)		Participants	Article type	Ref Nos.
			Brain activity	Oxy-Hb concentration in the prefrontal cortex (measured using NIRS) Increase: "strong" smell of α-pinene Decrease: "slight" smell of α-Pinene †Comparison with pre-stimulation	α-Pinene ("slight" and "strong" smell)	(90 s)	–		
			Autonomic nervous activity	Plus rate Increase: "strong" smell of α-pinene Systolic blood pressure Decrease: "slight" smell of α-pinene †Comparison with pre-stimulation					
			Autonomic nervous activity	Decrease in systolic blood pressure †Comparison with pre-stimulation	Limonene	(90 s)	–		
			Autonomic nervous activity (Ref No.[49])	Decrease in heart rate Decrease in systolic and diastolic blood pressure Inhibition of sympathetic nervous activity Enhancement of parasympathetic nervous activity *Comparison with control	Cedrol/air	–	–		
		Inhalation (lower airway)	Autonomic nervous activity (Ref No. [52])	Decrease in systolic and diastolic blood pressure Inhibition of sympathetic nervous activity Enhancement of parasympathetic nervous activity †Comparison with pre-stimulation	Cedrol	–	–		
2011	Miyazaki et al.	Vision	Autonomic nervous activity (Ref Nos. [62, 63])	Decrease in pulse rate Decrease in diastolic blood pressure †Comparison with pre-stimulation	Actual rooms (13 m^2) (30% wood)	–	–	Review (in Japanese with English abstract)	[66]
			Autonomic nervous activity (Ref No. [61])	Systolic blood pressure Evaluated the Japanese wall panels "Like" group: decrease "Dislike" group: no change †Comparison with pre-stimulation	Full-sized Japanese cypress wall panels/white steel wall panels	–	–		

Table 1 continued

Year	Authors	Sense	Physiological indices	Summary	Stimulation/control (stimulation time)		Participants	Article type	Ref Nos.
2011	Matsubara et al.	Olfaction	Brain activity	After performance of a sustained task on a VDT	Siberian fir leaf oil/air	(40 min)	Male univ. students $n = 9$	Original article	[55]
				Decrease in alpha band power					
				Increase in theta band power					
				*Comparison with control					
			Autonomic nervous activity	After performance of a sustained task on a VDT					
				Decrease in pulse rate					
				*Comparison with control					
2011	Matsubara et al.	Olfaction	Brain activity	After performance of a sustained task on a VDT	(-)-Bornyl acetate (low and high concentrations)/air	(40 min)	Male univ. students $n = 9$	Original article	[56]
				Increase in theta band power:low and high conc.					
				*Comparison with control					
			Autonomic nervous activity	During performance of a sustained task on a VDT					
				Decrease in heart rate: high conc.					
				*Comparison with control					
				After performance of a sustained task on a VDT					
				Decrease in heart rate: low and high conc.					
				Inhibition of sympathetic nervous activity: low and high conc.					
				†Comparison with task period 30 min					
2011	Matsubara et al.	Olfaction	Autonomic nervous activity	During performance of a sustained task on a VDT	Bay tree leaf oil (low and high concentrations)/air	(45 min)	Male univ. students $n = 9$	Original article	[57]
				Increase in heart rate: low and high conc.					
				*Comparison with control					
			Other indices	During performance of a sustained task on a VDT					
				Increase in rate of true hits: low conc.					
				*Comparison with control					
2011	Kimura et al.	Vision and olfaction (complex)	Autonomic nervous activity	Decrease in salivary amylase activity: wooden room (coverage 20.6%)	Actual-size model Hiba wooden rooms (coverage 20.6, 42.8, and 68.0%)/no Hiba wood room (0.0%)	(180 s)	Univ. students $n = 14$ (male $n = 7$, female $n = 7$)	Original article (in Japanese with English abstract)	[65]
				*Comparison with control					
				Decrease in systolic and diastolic blood pressure: wooden rooms (20.6, 42.8, and 68.0%)					
				†Comparison with pre-stimulation					

Table 1 continued

Year	Authors	Sense	Physiological indices	Summary	Stimulation/control (stimulation time)		Participants	Article type	Ref Nos.
2010	Tsunetsugu et al.	Olfaction	Brain activity	Decrease in oxy-Hb concentration in the prefrontal cortex (measured using NIRS) Decrease in total-Hb concentration in the prefrontal cortex (measured using NIRS) †Comparison with pre-stimulation	Japanese mountain cherry wood chips	(2 min)	Males of twenties $n = 20$	Original article (in Japanese with English abstract)	[42]
			Autonomic nervous activity	Decrease in pulse rate Decrease in salivary amylase activity †Comparison with pre-stimulation					
2010	Tsunetsugu et al.	Vision	Autonomic nervous activity (Ref Nos. [62–64])	Plus rate Increase: 45% wood; decrease: 30% wood Systolic blood pressure Decrease: 90% wood Diastolic blood pressure Decrease: 30 and 90% wood †Comparison with pre-stimulation	Actual rooms (13 m^2) (30, 45, and 90% wood)	–	–	Review	[35]
		Olfaction	Brain activity (Ref No. [41])	Increase in the amplitude of the early and late CNV components *Comparison with control	Hiba oil/air	–	–		
			Autonomic nervous activity (Ref No. [21])	Decrease in systolic blood pressure †Comparison with pre-stimulation	Taiwan cypress wood oil	–	–		
			Autonomic nervous activity (Ref No. [49])	Decrease in heart rate Decrease in systolic and diastolic blood pressure Inhibition of sympathetic nervous activity Enhancement of parasympathetic nervous activity *Comparison with control	Cedrol/air	–	–		
		Inhalation	Autonomic nervous activity (Ref No. [52])	Decrease in systolic and diastolic blood pressure Inhibition of sympathetic nervous activity Enhancement of parasympathetic nervous activity †Comparison with pre-stimulation	Cedrol	–	–		
		Taction	Autonomic nervous activity (Ref No. [75])	Blood pressure increase: warmed aluminum No change: cold oak †Comparison with pre-stimulation	Cold oak and warmed aluminum	–	–		

Table 1 continued

Year	Authors	Sense	Physiological indices	Summary	Stimulation/control (stimulation time)		Participants	Article type	Ref Nos.
2010	Nyrud and Bringslimark	Taction	Autonomic nervous activity (Ref No. [75])	Systolic blood pressure Increase: aluminum, acrylic plastic, and cold acrylic plastic board No change: cedar, cypress, and oak board Decrease: cold oak board †Comparison with pre-stimulation	Japanese cypress, Japanese cedar, oak, acrylic plastic, and aluminum (cool, room temperature, and warm)	–	–	Review	[68]
			Autonomic nervous activity (Ref No. [74])	Systolic blood pressure and pulse rate Small fluctuation: Japanese cypress and cedar Large fluctuation: stainless steel and denim	Japanese cypress, Japanese cedar, stainless steel board, and denim	–	–		
		Vision	Brain activity (Ref No. [64])	Total-Hb concentration in the prefrontal cortex (measured using NIRS) Increase: 0 and 90% wood No change: 45% wood †Comparison with pre-stimulation	Actual rooms (13 m^2) (0, 45, and 90% wood)	–	–		
			Autonomic nervous activity (Ref No. [64])	Plus rate Increase: 45% wood No change: 0 and 90% wood Systolic blood pressure Decrease: 90% wood No change: 0 and 45% wood Diastolic blood pressure Decrease: 0, 45, and 90% wood †Comparison with pre-stimulation					
			Autonomic nervous activity (Ref No. [61])	Systolic blood pressure Evaluated the Japanese wall panels "Like" group: decrease "Dislike" group: no change Evaluated the white steel wall panels "Dislike" group: increase †Comparison with pre-stimulation	Full-sized Japanese cypress wall panels/white steel wall panels	–	–		
			Brain activity (Ref No. [63])	Total-Hb concentration in the prefrontal cortex (measured using NIRS) Increase: standard and designed room †Comparison with pre-stimulation	Standard and designed wooden room	–	–		

Table 1 continued

Year	Authors	Sense	Physiological indices	Summary	Stimulation/control (stimulation time)	Participants	Article type	Ref Nos.
			Autonomic nervous activity (Ref No. [63])	Pulse rate Decrease: standard room Increase: designed room Diastolic blood pressure No change: designed room Decrease: Standard room †Comparison with pre-stimulation				
2009	Li et al.	Olfaction	Immune activity	Increase in natural killer cell activity †Comparison with pre-stimulation	Japanese cypress wood oil (3 nights)	Adult male $n = 12$	Original article	[37]
			Endocrine activity	Decrease in adrenaline concentration in urine Decrease in noradrenaline concentration in urine †Comparison with pre-stimulation				
2008	Sakuragawa et al.	Taction	Autonomic nervous activity	Systolic blood pressure Increase: aluminum, acrylic plastic, and cold acrylic plastic board No change: cedar, cypress, and oak board Decrease: cold oak board †Comparison with pre-stimulation	Japanese cypress, Japanese cedar, oak, acrylic plastic, and aluminum (cool, room temperature, and warm) (60 s)	Male univ. students $n = 13$	Original article	[75]
2008	Umeno et al.	Inhalation	Autonomic nervous activity	Decrease in systolic and diastolic blood pressure Inhibition of sympathetic nervous activity (measured using HRV) Enhancement of parasympathetic nervous activity (measured using SBPV and DBPV) †Comparison with pre-stimulation	Cedrol (10 min)	Totally laryngectomized male participants $n = 11$	Original article	[52]
2007	Sadachi et al.	Olfaction	Autonomic nervous activity	Increase in miosis rate †Comparison with pre-stimulation	Cedrol (60 s)	American females $n = 142$	Original article	[51]
2007	Yada et al.	Olfaction	Autonomic nervous activity	Increase in miosis rate †Comparison with pre-stimulation	Cedrol (60 s)	Females $n = 178$ (Japanese $n = 64$, Thai $n = 57$, Norwegian $n = 57$)	Original article	[50]

Table 1 continued

Year	Authors	Sense	Physiological indices	Summary	Stimulation/control (stimulation time)		Participants	Article type	Ref Nos.
2007	Tsunetsugu et al.	Vision	Brain activity	Total-Hb concentration in the prefrontal cortex (measured using NIRS)	Actual rooms (13 m^2) (0, 45, and 90% wood)	(90 s)	Male univ. students $n = 15$	Original article	[64]
				Increase: 0 and 90% wood					
				No change: 45% wood					
				†Comparison with pre-stimulation					
			Autonomic nervous activity	Plus rate					
				Increase: 45% wood					
				No change: 0 and 90% wood					
				Systolic blood pressure					
				Decrease: 90% wood					
				No change: 0 and 45% wood					
				Diastolic blood pressure					
				Decrease: 0, 45, and 90% wood					
				†Comparison with pre-stimulation					
2007	Tsunetsugu et al.	Vision	Autonomic nervous activity (Ref Nos. [63, 64])	Plus rate	Actual rooms (13 m^2) (30, 45, and 90% wood)	(90 s)	–	Review (in Japanese)	[67]
				Increase: 45% wood; decrease: 30% wood					
				Systolic blood pressure					
				Decrease: 90% wood					
				Diastolic blood pressure					
				Decrease: 30 and 90% wood					
				†Comparison with pre-stimulation					
		Audition	Autonomic nervous activity (Ref No. [71])	Systolic blood pressure	Single heavy floor impact sound (falling of an automobile tire from 50, 100, and 150 cm above upstairs floor)	–	–		
				Increase: 50, 100 and 150 cm					
				Peripheral blood flow					
				Decrease: 50, 100 and 150 cm					
				†Comparison with pre-stimulation					
2005	Sakuragawa et al.	Vision	Autonomic nervous activity	Systolic blood pressure	Full-sized Japanese cypress wall panels/white steel wall panels	(90 s)	Male univ. students $n = 14$	Original article	[61]
				Evaluated the Japanese wall panels					
				"Like" group ($n = 5$): decrease					
				"Dislike" group ($n = 5$): no change					
				Evaluated the white steel wall panels					
				"Dislike" group ($n = 9$): increase					
				†Comparison with pre-stimulation					

Table 1 continued

Year	Authors	Sense	Physiological indices	Summary	Stimulation/control (stimulation time)		Participants	Article type	Ref Nos.
2005	Tsunetsugu et al.	Vision	Brain activity	Total-Hb concentration in the prefrontal cortex (measured using NIRS) Increase: standard and designed room †Comparison with pre-stimulation	Standard and designed wooden room	(90 s)	Male univ. students $n = 15$	Original article	[63]
			Autonomic nervous activity	Pulse rate Decrease: standard room Increase: designed room Diastolic blood pressure No change: designed room Decrease: standard room †Comparison with pre-stimulation					
2004	Sueyoshi et al.	Audition	Autonomic nervous activity	Systolic blood pressure Increase: 60 and 80 dBA †Comparison with pre-stimulation	Light floor impact sounds by tapping machine (60 and 80 dBA)/absence of impact sound (47 dBA)	(5 min)	Males of twenties $n = 9$	Original article	[70]
2004	Sueyoshi et al.	Audition	Autonomic nervous activity	Systolic blood pressure Increase: 50, 100, and 150 cm Peripheral blood flow Decrease: 50, 100, and 150 cm †Comparison with pre-stimulation	Single heavy floor impact sounds by falling of the automobile tire (from 50, 100, and 150 cm above upstairs floor)	(60 s)	Males in 20s $n = 10$	Original article	[71]
2004	Sueyoshi	Audition	Autonomic nervous activity (Ref No. [71])	Systolic blood pressure Increase: 50, 100 and 150 cm Peripheral blood flow Decrease: 50, 100 and 150 cm †Comparison with pre-stimulation	Single heavy floor impact sounds from a falling automobile tire (from 50, 100, and 150 cm above the upstairs floor)	–	–	Review (in Japanese with English abstract)	[73]
			Autonomic nervous activity (Ref No. [70])	Systolic blood pressure Increase: 60 and 80 dBA †Comparison with pre-stimulation	Light floor impact sounds by tapping machine (60 and 80 dBA)/absence of impact sound (47 dBA)	–	–		
2003	Dayawansa et al.	Olfaction	Autonomic nervous activity	Decrease in heart rate Decrease in systolic and diastolic blood pressure Inhibition of sympathetic nervous activity (measured using HRV) Enhancement of parasympathetic nervous activity (measured using HRV) *Comparison with control	Cedrol/air	(10 min)	Adults $n = 26$ (male $n = 10$, female $n = 16$)	Original article	[49]
2002	Tsunetsugu et al.	Vision	Autonomic nervous activity	Decrease in pulse rate *Comparison with designed wooden room	Standard wooden room/designed wooden room	(90 s)	Male univ. students $n = 10$	Original article	[62]
2002	Hiruma et al.	Olfaction	Brain activity	Increase in the amplitude of the early and late CNV components *Comparison with control	Hiba oil/air	(30 min)	Females of twenties $n = 16$	Original article	[41]

Table 1 continued

Year	Authors	Sense	Physiological indices	Summary	Stimulation/control (stimulation time)		Participants	Article type	Ref Nos.
1998	Morikawa et al.	Taction	Autonomic nervous activity	Systolic blood pressure and pulse rate Small fluctuation: Japanese cypress and cedar Large fluctuation: stainless steel and denim	Japanese cypress, Japanese cedar, stainless steel board, and denim	(60 s)	Female univ. students $n = 19$	Short communication	[74]
1998	Miyazaki et al.	Olfaction	Autonomic nervous activity (Ref No. [21])	Systolic blood pressure Decrease: Taiwan cypress wood oil Pulse rate Increase: eugenol †Comparison with pre-stimulation	Taiwan cypress wood oil and eugenol	–	–	Review (in Japanese)	[59]
1996	Terauchi et al.	Olfaction	Brain activity	Early CNV amplitudes at Fz Decrease: 7 kinds of coniferous wood flour Alpha/beta wave ratio of EEG at Cz Increase: Hiba wood flour *Comparison with control	Seven kinds of coniferous wood flour/air	–	Univ. and grad. students $n = 10$ (male $n = 5$, female $n = 5$)	Original article (in Japanese with English abstract)	[40]
1995	Sueyoshi and Miyazaki	Audition	Brain activity	Alpha waves of EEG Decrease: 74 and 78 dBA Theta waves of EEG Decrease: 63 dBA *Comparison with control	Light floor impact sounds by tapping machine (54, 63, 73, and 78 dBA)/absence of impact sound (47 dBA)	(90 s)	Female $n = 14$	Original article	[69]
			Other indices	Operation efficiency test (letter cancellation test) Increase mistake: 65 dBA *Comparison with control					
1995	Fukuda and Kaneko	Olfaction	Brain activity	Incidence of alpha waves of EEG Increase: Japanese umbrella-pine, Japanese white pine, and Japanese zelkova †Comparison with pre-stimulation	Wood specimen of 15 species of major trees in Japan	(2 min)	Univ. students $n = 50$ (male $n = 25$, female $n = 25$)	Original article (in Japanese)	[43]
1994	Miyazaki et al.	Olfaction	Autonomic nervous activity	Diastolic blood pressure decrease: "strong" smell of Taiwan cypress wood oil The maximum constriction acceleration Increase: "strong" smell of Taiwan cypress wood oil *Comparison the control	Taiwan cypress wood oil ("weak", "easily", and "strong" smell)/air	–	Female univ. students $n = 6$	Original article (in Japanese with English abstract)	[36]
1993	Miyazaki et al.	Olfaction	Autonomic nervous activity (Ref No. [21])	Systolic blood pressure Decrease: Taiwan cypress wood oil Pulse rate Increase: eugenol †Comparison with pre-stimulation	Taiwan cypress wood oil and eugenol	–	–	Review (in Japanese)	[58]

Table 1 continued

Year	Authors	Sense	Physiological indices	Summary	Stimulation/control (stimulation time)	Participants	Article type	Ref Nos.
1992	Miyazaki et al.	Olfaction	Autonomic nervous activity	Systolic blood pressure Decrease: Taiwan cypress wood oil Pulse rate Increase: eugenol †Comparison with pre-stimulation	Taiwan cypress wood oil and eugenol (30 min)	Male univ. students $n = 6$	Original article (in Japanese with English abstract)	[21]

CNV contingent negative variations; *conc.* concentration, *DBPV* diastolic blood pressure variability, *EEG* electroencephalogram, *HRV* heart rate variability, *NIRS* near-infrared spectroscopy, *oxy-Hb* oxy-hemoglobin, *rCBF* regional cerebral blood flow, *SBPV* systolic blood pressure variability, *SPET* single-photon emission tomography, *TRS* time-resolved spectroscopy, *U-K test* Uchida–Kraepelin test, *univ.* university, *VDT* visual display unit

effects on humans have only recently begun to be collected.

In 1992, Miyazaki et al. [21] examined the effect of olfactory stimulation by Taiwan cypress (*Chamaecyparis taiwanensis*) wood oil and eugenol on blood pressure, pulse rate, coefficient of variation of R–R intervals in the electrocardiogram (ECG), and performance (letter cancellation test). The participants were six male university students aged between 21 and 22 years, and the experiment was conducted in an artificial climate chamber with the temperature set at 25 °C and humidity at 60%. The strength of perceptibility of the stimulus was adjusted from "easily sensed" to "slightly sensed" on average, and the stimulation was administered for a duration of 30 min. After olfactory stimulation by the Taiwan cypress wood oil, the systolic blood pressure of the participants decreased by 6%, which is considered a meaningful reduction (for comparison, the difference between the high-normal blood pressure of 130 mmHg and normal blood pressure of 120 mmHg is 8.3%). Task performance increased on average by 4%, although this change was not statistically significant. In contrast, in tests using eugenol, a component of the clove oil used in dental disinfectants and rated as "uncomfortable" to smell, olfactory stimulation resulted in an increase in pulse rate of 6%. In 1994, Miyazaki et al. [36] investigated the effects of the different concentration of Taiwan cypress wood oil on blood pressure, pupillary light reflex, and performance. Six female university students aged between 21 and 27 years (mean 22.0 years) participated in this study. To test the perceptibility of the stimulus, three concentrations of Taiwan cypress wood oil were established: "weak", "easily sensed", and "strong". The experiment was conducted in a soundproof artificial climate chamber with the temperature, humidity, and illuminance set at 25 °C, 50%, and 230 lx, respectively. After olfactory stimulation with Taiwan cypress wood oil rated as a "strong" smell, the participants' diastolic blood pressure decreased by 8% and their maximum constriction acceleration, which reflects autonomic nervous activity, increased by 17%. There was no significant difference; however, the task performance increased by approximately 10% on average.

Li et al. [37] examined the effects of Japanese cypress (*Chamaecyparis obtusa*) wood oils on endocrine and immune activity. The participants were 12 male instructors aged between 37 and 60 years who worked at a university, who stayed for three nights in a room at an urban hotel where Japanese cypress wood oil was vaporized with a humidifier. After this, the concentrations of adrenaline and noradrenaline in the participants' urine were reduced and natural killer cell activity was induced. Thus, olfactory stimulation by Japanese cypress wood oil brought about improvements in immune functions.

Several studies have focused on olfactory stimulation with Japanese cedar (*Cryptomeria japonica*), a common and familiar coniferous tree in Japan. Tsunetsugu et al. [38] revealed the effects of olfactory stimulation by Japanese cedar wood chips on the prefrontal cortex activity and blood pressure of 14 male university students. The participants were seated in an indoor artificial climate chamber with the temperature, humidity, and illuminance set at 25 °C, 60%, and 50 lx, respectively. Olfactory stimuli were presented to the participants as follows: the Japanese cedar chips were placed into a smell bag; this bag was filled with 24 L of indoor air, which became saturated with volatile compounds from the chips; and a smell supply device delivered a flow of 2–3 L/min of this scented air approximately 15 cm under the participant's nose. The strength of perceptibility of the stimulus was adjusted from "weak" to "slightly sensed" on average, and the duration of the stimulation was approximately 60–90 s. Following this olfactory stimulation with Japanese cedar chips, the participants showed a reduction of total hemoglobin (total Hb) concentration in the left and right prefrontal cortex and decreased systolic blood pressure, indicating that the olfactory stimulation had a physiologically relaxing effect. Matsubara and Kawai [39] investigated the effects of olfactory stimulation with the volatile organic compounds emitted from interior walls made of Japanese cedar on 16 male university students aged between 21 and 28 years (mean 23.5 years), who performed arithmetic tasks (the Uchida–Kraepelin test) for repeated cycles of 15 min of work and 5 min of rest. As a control, the participants undertook similar work in a room without Japanese cedar interior wall panels. Under the control condition, the participants' salivary chromogranin A concentration, which is known to be a stress marker, was higher after completing the task than before the task. In contrast, the change between pre- and post-work measurements under the Japanese cedar condition was not significant.

There have been several studies using hiba (*Thujopsis dolabrata*) wood flour and essential oil as olfactory stimulation. Terauchi et al. [40] examined the effects of olfactory stimulation of hiba wood flours on contingent negative variation (CNV) and EEG readings. The participants were ten university and graduate students (five male and five female) aged between 20 and 26 years. The strength of perceptibility of the stimulus was adjusted to "easily sensed" on average. The results of olfactory stimulation with hiba flours showed a decrease in the early CNV amplitudes at the frontal midline (Fz) and an increased EEG alpha/beta wave ratio at the vertex of the head (Cz), indicating that this olfactory stimulation had a calming effect. However, contradictory results have also been reported. Hiruma et al. [41] investigated the influence on CNV of olfactory stimulation by hiba oil. Although the sensory intensity was not indicated in the report, the amplitude of the early and late CNV components were larger, and the reaction time to a click–flash task shorter, under the hiba oil condition than under the control condition with an absence of olfactory stimulation. This indicates that olfactory stimulation with hiba oil had an awakening effect.

Other types of wood have been studied. Tsunetsugu et al. [42] investigated the effects of olfactory stimulation with Japanese mountain cherry (*Cerasus jamasakura*) wood chips on prefrontal cortex activity and autonomic nervous activity in 20 male university students (mean age 24.2 years). The strength of perceptibility of the stimulus was adjusted to "easily sensed", and the duration of the stimulation was 2 min. Olfactory stimulation by Japanese mountain cherry wood chips reduced oxy-Hb concentration in prefrontal cortex, pulse rate, and salivary amylase activity. Using EEG, Fukuda and Kaneko [43] examined the effects of olfactory stimulation on brain activity by wood specimens from 15 major species of tree found in Japan. Olfactory stimulation by Japanese umbrella-pine (*Sciadopitys verticillata*), Japanese white pine (*Pinus parviflora* var. *parviflora*), and Japanese zelkova (*Zelkova serrata*) resulted in an increased incidence of alpha waves at the post-stimulation measurement compared with the pre-stimulation measurement, indicating that these olfactory stimulations had a calming effect.

The different olfactory effects on human physiology that result from different wood-drying methods have also been investigated. Ikei et al. [44] compared the physiological effects of olfactory stimulation by air-dried and high-temperature-dried Japanese cypress chips. The air-dried wood was produced through natural drying processes over 45 months. The high-temperature-dried wood was produced using steam heating drying equipment, which can dry at a high temperature and high speed. The experiment was conducted with 19 female university students (mean age 22.5 years) in a soundproof artificial climatic chamber with the temperature, humidity, and illuminance set at 25 °C, 50%, and 230 lx, respectively. The Japanese cypress chips (80 g) were placed into a smell bag, the smell bag was filled with 24 L of indoor air, and the air saturated with volatile compounds of chips was delivered at a flow of 3 L/min approximately 10 cm under the participant's nose using a smell supply device. A crossover trial to eliminate any effects due to the order of olfactory stimulation was performed. Ten of the participants were administrated the olfactory stimulation condition first followed by the control condition. The other nine participants received the control first and then the olfactory stimulation. The strength of perceptibility of the stimulus was adjusted from "weak" to "slightly sensed" on average, and the oxy-Hb concentrations in the prefrontal cortex of the participants was measured using near-infrared time-resolved spectroscopy (TRS) throughout the 90-s duration of stimulation. Olfactory stimulation by air-dried wood chips reduced the oxy-Hb concentrations in the right and left prefrontal cortices, whereas these remained unchanged with the high-temperature-dried wood chips; the difference between the two stimulations was statistically significant. This clarified that the prefrontal cortex activity by olfactory stimulation by wood varied according to the wood-drying method.

Single substance inhalation experiments using the main volatile components of wood such as α-pinene and limonene have also been conducted following the same experimental design as in the reports already described [38, 45, 46]. Tsunetsugu et al. [38] investigated the effects of olfactory stimulation by α-pinene and limonene on blood pressure. The strength of perceptibility of the stimulus was adjusted to "slightly sensed" on average, and the blood pressure of the participants was measured every second throughout the 90-s duration of stimulation. Inhalation of α-pinene and limonene reduced systolic blood pressure. Joung et al. [45] also examined olfactory stimulation by D-limonene on autonomic nervous activity by using HRV as an indicator in 13 female university students (mean age 21.5 years). HRV measurements provides two important results: the high-frequency (HF) power, which reflects parasympathetic nervous activity (known to increase during relaxation); and the ratio of low-frequency (LF) to HF, presented as either LF/HF or LF/(LF + HF), which reflects sympathetic nervous activity (known to increase during arousal or stress). In this study, inhalation of D-limonene for 90 s increased HF power by 26.4%. It also reduced the heart rate compared with the control condition (air), suggesting that D-limonene induces physiological relaxation effects. No significant difference was observed in the LF/HF ratio. Ikei et al. [46] investigated the physiological effect of olfactory stimulation on heart rate variability with α-pinene. Inhalation of this for 90 s increased parasympathetic nervous activity by 46.8% and reduced heart rate by 2.8% compared with control (air), indicating physiological relaxation. No significant difference was observed in the LF/(LF + HF) ratio. For comparison, research on forest therapy [10] found an increase in HF power to 102.7% from walking in forests and 55.0% from viewing forest scenery, indicating substantial physiological relaxation effects. In addition, a difference of 21% has been reported when viewing fresh rose flowers [47], and 19.2% when smelling the scent of fresh rose flowers [48] from a sitting position.

Several studies have been conducted in Japan involving inhalation of cedrol, a major component of Japanese cedar tree wood. Dayawansa et al. [49] reported the effects of olfactory stimulation by cedrol on the autonomic nervous activity of 26 Japanese participants (10 male and 16 female, mean age 24 years). The participants were exposed to olfactory stimulation by cedrol for 10 min. This reduced the participants' heart rate, systolic and diastolic blood pressure, suppressed sympathetic nervous activity, and enhanced parasympathetic nervous system activity compared with the control condition (air). Yada [50] examined effects of olfactory stimulation by cedrol on the autonomic nerve activity of Norwegian, Thai, and Japanese females. The miosis rate (the ratio of the change in pupil diameter after a light stimulus to the initial pupil diameter) in the pupillary light reflex was measured before and after cedrol inhalation. The miosis rate increased after cedrol exposure in the subjects of all three nationalities, suggesting that parasympathetic nervous activity had become dominant. Sadachi et al. [51] investigated the effects of olfactory stimulation by cedrol on the autonomic nerve activity of American female, following the same experimental design. In addition, Umeno et al. [52] investigated the effects on the autonomic nerve activity of direct cedrol inhalation into the lower airway in 11 males who had undergone a total laryngectomy. Compared to the pre-stimulation condition (air), direct inhalation of cedrol for 10 min reduced the participants' systolic and diastolic blood pressure and sympathetic nervous activity, and increased their parasympathetic nervous activity. Following the same experimental design with the same laryngectomized participants, Hori et al. [53] investigated the effects of direct cedrol inhalation on brain activity, using regional cerebral blood flow (rCBF) measured with single-photon emission tomography as the index of brain activity. The rCBF of the hippocampus, an important area in the regulation of emotion and stress, was increased bilaterally during cedrol inhalation.

There have also been studies about the effects of olfactory stimulation by tree leaves. Ikei et al. [54] investigated the effects of olfactory stimulation by Japanese cypress leaf oil on brain activity and autonomic nervous activity following the same experimental design as in the studies of Ikei et al. and Joung et al. already described [44, 45]. The participants were 13 female university students (mean age 21.5 years). Olfactory stimulation by Japanese cypress leaf oil induced a reduction in oxy-Hb concentration in the right prefrontal cortex and increased parasympathetic nervous activity (the HF power of HRV) by 34.5% compared to the control condition, indicating that olfactory stimulation by Japanese cypress leaf oil can induce physiological relaxation. Matsubara et al. [55] examined the effects on brain and autonomic nervous activity of Siberian fir (*Abies sibirica*) leaf oil during and after the performance of a sustained task on a visual display terminal (VDT). Nine male university students (mean age 22 years) inhaled air (control condition) or the odorant (Siberian fir leaf oil condition) for a total of 40 min (a

5-min baseline before performing the task, a 30-min VDT task, and a 5-min recovery period after the task). Compared with the control condition, the participants' heart rate and alpha band power after the task in the presence of Siberian fir leaf oil were decreased and the theta band power was increased. Matsubara et al. [56] also investigated the effects of (−)-bornyl acetate, one of main components contained in the leaves of the Siberian fir, following the same experimental design. After the VDT task in the presence of (−)-bornyl acetate, the sympathetic nervous activity was decreased and the theta band powers increased compared with task performed under the control condition. However, it has been reported that olfactory stimulation by bay tree (*Laurus nobilis*) leaves increased heart rate compared to the control (air) [57].

There were 20 papers reporting studies about olfactory stimulation. Across all of these papers, the number of participants ranged from 6 to 178; however, the number of participants in 15 of these papers ranged from 6 to 19. The participants were aged from 20 to 60 years, but 15 papers included only participants in their 20s. The exposure times to stimulation ranged from 60 s to 3 days, including 60–120 s in eight papers and 10–45 min in nine papers. Notably, in ten papers there was no statistical comparison between stimulation and a control condition, with comparisons made only between pre- and post-stimulation.

In addition to these individual studies, there have been several reviews of olfactory stimulation by wood-derived substances [5, 35, 58–60].

Visual stimulation

Studies investigating the effects of visual stimulation of wood have included experiments with wood panels and wooden rooms.

Sakuragawa et al. [61] examined the effects on systolic and diastolic blood pressure of visual stimulation by full-sized Japanese cypress wall panels. The control was white steel wall panels of a similar size. Fourteen male university students individually viewed each type of wall panel for 90 s while sitting in a chair. The participants were then asked to rate the wall panels according to whether they liked them or not. Over the whole group, there was no significant difference in the results for the two types of panel. However, during the visual stimulation involving the Japanese cypress wall panels, systolic blood pressure decreased among the participants who evaluated the Japanese cypress wall panels as "like", whereas there was no change among the participants who evaluated them as "dislike". For the white steel wall panels, systolic blood pressure increased in the participants who evaluated them as "dislike".

The physiological effects of visual stimulation by wooden room interiors have also been reported. Tsunetsugu et al. [62–64] investigated the difference in physiological effects of visual stimulation by rooms with different designs and proportions of wood. Actual rooms (13 m^2) were built for the study. Living rooms in Japan typically contain approximately 30% wood in their structure. For this study, four actual rooms (all with area 13 m^2) were built: a typical wooden living room (30% wood), a room with extra wood added to the walls (45% wood), and a room where almost all of the wall and the entire floor and ceiling were covered with wood (90% wood). Fifteen male university students aged between 19 and 28 years were exposed to the visual stimulation of each room interior for 90 s. Systolic blood pressure, diastolic blood pressure, and pulse rate were continuously measured as an index of physiological reaction. Visual stimulation by the 30% wood room reduced the participants' diastolic blood pressure and pulse rate, suggesting that this room induced physiological relaxation effects. In contrast, visual stimulation by the 45% wood room increased pulse rate. In a 30% wood room with added wooden pillars and cross-beams (a designed room taking the total wood content to 40%), the participants' pulse rates increased in a manner similar to that in the room with 45% wood, indicating a state of physiological wakefulness. In the participants' subjective evaluations, they rated all the wooden room interiors as "comfortable". These findings demonstrated that variations in the percentage of wood and the design of a wooden living room induced different physiological changes, and suggested that visual stimulation by a room with 30% wood, which is a standard type of living room commercially available in Japan, induced a physiological relaxation effect.

Kimura et al. [65] examined the different effects of visual and olfactory stimulation by four actual-size model rooms (width 2700, depth 3550, and height 2380 mm) that contained different proportions of hiba wood. Systolic blood pressure, diastolic blood pressure, pulse rate, and salivary alpha-amylase were continuously measured as an index of physiological reaction in seven male and seven female university students (mean age 19.9 years). Systolic and diastolic blood pressure decreased following visual and olfactory stimulation by all four rooms. Furthermore, visual and olfactory stimulation by the room with hiba wood coverage of 20.6% resulted in lower salivary amylase activity compared with stimulation by the room with no hiba wood. These results show that different amounts of hiba wood in interior rooms have different effects on autonomic nervous activity. However, the extent of the separate contributions of the visual and the olfactory stimuli to the physiological response are unknown because the participants received both types of stimulation simultaneously in this experiment.

In total, four papers reported the studies of visual stimulation. These included 10–15 participants aged in their 20s, and the exposure times to stimulation ranged from 90 to 120 s. Three of the four studies did not include a statistical comparison between stimulation and a control condition, but instead conducted statistical comparisons only between pre- and post-stimulation.

In addition to these individual studies, there have been several reviews of wood-derived visual stimulation [5, 34, 35, 38, 60, 66–68].

Auditory stimulation

Investigation of the effects of auditory stimulation by wood on physiological response included experiments on floor impact sounds in a wooden house.

Sueyoshi et al. [69, 70] examined effects of light floor impact sounds on the EEG and on the systolic and diastolic blood pressure of 14 males aged between 24 and 29 years. The measurements were conducted in a Japanese style room in an experimental two-storied wooden house. Sitting on a chair at the center of the downstairs room, each participant was exposed to light floor impact sounds that were generated for 5 min on the upstairs floor by a tapping machine. Four light floor impact sounds at 54, 63, 73, and 78 dBA and control (the absence of an impact sound, leaving the average background noise level of 47 dBA) were generated randomly for each participant. This showed that as the light floor impact sound level increased, the incidence of alpha and theta waves on the EEG decreased [69], and that an increase in systolic blood pressure immediately after exposure to the light floor impact sounds depended on the level of the sounds [70].

Sueyoshi et al. [71] also investigated the effects of a single heavy floor impact sound on systolic blood pressure and peripheral blood flow in ten males aged between 24 and 29 years. Each participant sat on a chair at the center of the downstairs room and was exposed to a single heavy floor impact sound generated on the upstairs floor with an automobile tire dropped from heights of 50, 100, and 150 cm. This test has been specified in JIS A 1418-2:2000 [72]. The single heavy floor impact sound generated by the tire increased systolic blood pressure and decreased peripheral blood flow, demonstrating that the human body enters a stress state in response to single heavy floor impact sounds.

In total, therefore, there were three papers about auditory stimulation, which included 9–14 participants aged in their 20s. The exposure times to stimulation ranged from 90 s to 5 min. None of the three papers included a statistical comparison between stimulation and a control condition, but instead conducted statistical comparisons only between pre- and post-stimulation.

In addition to the studies, there have been two reviews of auditory stimulation in a wooden house [67, 73].

Tactile stimulation

There have been very few previous reports about the physiological effects of contact with wood or wooden materials.

Morikawa et al. [74] examined the effects on systolic blood pressure and pulse rate of contact with wood or artificial substances. The participants were 19 female students aged between 20 and 29 years. The study showed that contact with a stainless steel plate or denim material resulted in great fluctuations in the systolic blood pressure and pulse rate, whereas contact with Japanese cypress and Japanese cedar wood caused little fluctuation.

Sakuragawa et al. [75] examined differences in the effects of tactile stimulation on human physiology that resulted from materials at different temperatures (cool, room temperature, and warm). Thirteen male university students each touched the surface of each material for 60 s with their eyes closed. This showed the following results: (1) contact with an aluminum plate increased blood pressure, but the increase was inhibited when the aluminum was warmed; (2) contact with an acrylic plastic plate increased blood pressure, with a greater rate of increase in blood pressure when the acrylic plastic plate was chilled; and (3) blood pressure did not change in response to contact with materials made of Japanese cypress, Japanese cedar, or oak (*Quercus crispula*), and did not increase even when the oak material was chilled. These results demonstrated that the temperature of the material has a considerable influence on the increase in blood pressure caused by contact with artificial materials such as metals and acrylic. In contrast, contact with wood does not increase blood pressure whether cold or at room temperature, showing its suitability as a material.

Only these two papers described tactile stimulation. They included 13 and 19 participants aged in their 20s. The exposure times to stimulation were 60 s in both cases, and both papers conducted statistical comparisons between pre- and post-stimulation only, with no control condition.

In addition, there have been four reviews of tactile stimulation involving wood-derived material [5, 35, 60, 68].

Summary of the physiological effects of stimulation by wood and wooden materials

This review has described scientific reports that elucidated the physiological effects of wood-derived stimulation.

Throughout, these reports showed that olfactory, visual, tactile, and auditory stimulation involving wood-derived materials induced physiological relaxation such as reduction of brain activity, enhancement of parasympathetic nervous activity, and inhibition of sympathetic nervous activity, as well as decreased blood pressure, heart rate, and stress hormone level.

Overall, 41 articles and reviews published in the 25-year period from 1992 to 2016 were included in this review. These were distributed across 5-year periods as follows: 5 (1992–1996), 2 (1997–2001), 9 (2002–2006), 15 (2007–2011), and 10 (2012–August 2016). It can be seen that reports about physiological effects of wood on humans have broadly increased gradually.

However, there are several limitations to these studies. First, the number of participants was generally small and a high proportion of the studies only recruited men and women in their 20s. To generalize the findings would require further studies based on larger samples with a greater range of ages (children to the elderly). Second, many studies used a single stimulus such as only olfactory stimulation or only visual stimulation. No study used complex stimulation. Third, in many studies the experimental design was incomplete, often without a control condition, thus basing results only on a comparison with pre-measurement values. Future studies based on an appropriate experimental design should be performed to accumulate data that can be extrapolated to everyday life.

Prospects for the future

It is known that physiological changes can be brought about by wood-derived stimuli, but the response can vary between individuals. It has been demonstrated that individual differences found in studies are not simply artifact but can have an important meaning in forest therapy research [76, 77]. Indeed, individual difference is an important issue for future studies researching the physiological effects of wood. In this section, we introduce the recent approach to explaining individual differences, which is of major importance in the future of wooden material therapy.

It is recognized that considerable individual differences are observed in physiological data related to nature therapy, including wooden material therapy, but there has not yet been a suitable approach for elucidating this variability. However, in forest therapy studies, attempts have been made to elucidate such individual differences using the "law of initial value" advocated by Wilder [78, 79]. This proposes the principle that the direction of the response to a stimulus depends largely on the initial value. Thus, the higher the initial value, the smaller the response to function-raising stimuli and the larger the response to function-depressing stimuli.

Song et al. [76, 77] investigated the individual differences in physiological relaxation effects related to forest therapy from the perspective of this "law of initial value" and showed that individual differences are not just variations but rather are physiological adjustment effects. The forest therapy experiment involved walking for 15 min in forest and urban areas in eight locations across Japan. The participants in each experiment location included 12 male university students in their 20s, with a total of 92 participants for whom data could be obtained (mean age 21.5 years), and the indicators measured were diastolic blood pressure and pulse rate [76]. For each participant, (value after walking) − (value before walking) was calculated for diastolic blood pressure; this showed that the majority of participants experienced reductions in blood pressure after walking in the forest. However, blood pressure increased in some participants, showing that there is great individual variation. The "law of initial value" was therefore applied and the relationship between the absolute value for the participant's blood pressure before walking in the forest (the initial value) and the change in blood pressure, i.e., (value after walking) − (value before walking), was investigated. This showed a negative correlation between the initial value and the change in value, indicating that blood pressure decreased after walking in the forest in participants whose initial values were high, and values increased in participants with low initial values. A similar relationship was found between the initial value and the change in pulse rate. In contrast, there was no correlation between the initial value and the change in value when the same participants walked in urban areas. Thus, it was concluded that walking in the forest entailed physiological adjustment effects that brought the diastolic blood pressure and pulse rate closer to their ideal values.

As described, the elucidation of individual differences has shown that the forest environment has a physiological adjustment effect. Individual differences in the physiological response to wood-derived stimulation should not be considered as artifact but should be regarded as substance. Elucidation of individual differences is an important research task in wooden material therapy. Future research on the effects of wood should seek to confirm and further clarify the physiological adjustment effect.

Conclusions

This review presented the recent research about the physiological effects of wood on humans. Data on the physiological effects of wood-derived stimulation are extremely limited, but during the last 15 years, physiological data related to wooden material therapy have rapidly accumulated in the context of advances in physiological measurement systems and measurement equipment. In the future, preventive medical effects by wood-derived stimulation, such as stress reduction and improvement in immune function, may potentially be explained through objective data obtained using a range of physiological indicators, including brain activity, autonomic nervous activity, endocrine activity, and immune activity.

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