Literature Review

Exploring the Impact of Wood Defects (Knots) on Human Psychology and Physiology: A Comprehensive Review

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This systematic literature review, inspired by (Harju, 2022), examines individuals' physiological and psychological responses to wood defects, which significantly contribute to substantial wood loss in mass timber construction. Following the SPAR-4-SLR protocol (Paul et al., 2021), the study employs the TCCM framework (Paul & Criado, 2020) to analyze literature from diverse fields and examine empirical studies from around the world. Using qualitative and quantitative methods, the research captures an evolving understanding of individuals' physiological and psychological reactions to wood and provides a comprehensive view of human-wood interaction. Findings are synthesized through the TCCM framework, highlighting theoretical foundations, varied contexts, and wood defect characteristics. This research contributes to the interdisciplinary discourse on wood defects' impact on human experiences, preferences, and well-being. It also helps lay the groundwork for determining if the aversion to wood with defects is a universal sentiment or if it is a learned preference specific to certain regions around the world. The identified research gaps pave the way for future investigations, emphasizing theory development, diverse contexts, distinct characteristics, and refined methodologies.

Keywords: *Wood Knots, Psychology, Physiology, Wood Defects*

1 Introduction

Mass timber construction has recently seen a surge in popularity, primarily due to its remarkable environmental benefits and superior building performance, offering transformative potential for the construction industry. However, the effects of this construction method from the occupants' perspective remain largely unexplored.(Whyte et al., 2024) Research has demonstrated that mass timber construction (MTC) can foster a comfortable indoor environment through its distinctive building attributes, such as enhanced ventilation and air quality, superior thermal comfort, effective acoustics, and optimal lighting.(Alapieti et al., 2020) (Ikei et al., 2017). Additionally, according to the biophilic hypothesis, humans have an inherent desire to connect with nature (Wilson, 2007), which fosters a positive perception of wood as a natural, warm, and health-promoting material.(Zhong et al., 2022) (Candido et al., 2021)

However, the forest resources available for mass timber construction are limited, and their sustainable management requires optimal use of the harvested material.(N. O. Broman, 2001a) This includes effective utilization of lower grades (material with defects). While the strength properties of these low- grade materials are a potential limitation, the stiffness properties of these materials is not as significantly compromised by the defects. In the structural design of mass timber floor systems, it is frequently the stiffness properties that govern the design.(Mirdad & Chui, 2020)Therefore an opportunity exists for increased utilization of low-grade materials in floor systems if the non-structural properties of these grades show similar performance to those of high-grade materials. One of these key non-structural properties is the biophilic benefits from timber construction. Numerous studies conducted over the years have focused on exploring the physiological and psychological responses of individuals when exposed to the biophilic element of wood and its environments. Interior coverings, including walls, ceilings, and floors, with wooden surfaces can influence both psychological and physiological responses (Jalilzadehazhari & Johansson, 2019). These responses encompass visual, auditory, olfactory, and tactile stimulation from interior wooden surfaces.

Research has identified a correlation between the presence of wood and improvements in both physiological and psychological states (Shigue, 2021). Preferences for environments rich in wood, including flooring, wall panels, ceilings, and furniture, are prevalent and intuitively linked to the positive effects associated with wood. Some studies have even found associations between the presence of wood and lower blood pressure, reduced stress levels, more positive emotions, and decreased depressive thoughts, with participants reporting sensations of warmth and induced calmness.

In a study (Demattè et al., 2018), it was revealed that wood induces more positive emotions than plaster. The research highlights the positive influence of wood on human psychological well-being and emphasizes the importance of considering

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multiple sensory modalities when investigating wood-human interaction.

Qualitative and quantitative approaches

In terms of research approaches, most papers indicate positive benefits in human health using qualitative/quantitative methods relying on surveys and questionnaires. Some studies utilize quantitative approaches, measuring physiological responses like heart rates, blood pressure, and skin conductance. For instance, David Robert Fell's research (Fell, 2010) employed the Paced Auditory Serial-Addition Task (PASAT) to induce stress and observe physiological and psychological responses. The study focused on monitoring physiological indicators to establish a tangible connection between wood presence and stress reduction.

Some studies go beyond singular approaches and adopt a mixed-methods strategy to enhance the depth of their findings. A notable illustration is the research (Douglas et al., 2022), where a combination of online survey research and a substantial laboratory experiment was employed. In this experiment, participants wore the Empatica E4® device on their left wrist, measuring and recording various physiological indicators such as heart rate, electro dermal activity (EDA), temperature, and motion. The study's outcomes indicated that exposure to natural materials substantially reduced immediate stress responses and fostered increased divergent creativity, especially among specific demographics within the participant group. This dual-method approach allowed for a more comprehensive understanding of the impact of natural materials on both physiological and psychological aspects, contributing valuable insights to the field.

Nevertheless, there is a shortage of systematic literature reviews exploring the physiological and psychological responses to specific wood characteristics, particularly wood defects like knots.

Wood defects

Since the ratification of The Paris Agreement at the United Nations in New York in 2016, nations globally have actively engaged in initiatives focused on resource conservation, enhanced energy efficiency, and diminished carbon emissions (Chen et al., 2023). In the practical realm of wood production, safeguarding forest resources and optimizing wood utilization have gained increased significance. Wood processing industries have consistently aimed to maximize yields in their operations, thereby minimizing volume loss of wood (N. O. Broman, 2001a). Notably, within wood processing, only 50 to 70% of logs are utilized after the removal of defects, bark, and branches (Zhuang, 2010). It is essential to consider the increased utilization potential for wood and the impact of wood defects in this context.

(a) Live Knots (b) Dead Knots (c) Pest Damage

Figuure 1. Wood. Defects Source: Sang, 2013

Wood defects primarily fall into three categories: growth defects resulting from physiological factors, damage induced by pests due to pathological reasons, and defects arising from processing influenced by human factors (Sang, 2013). Among the growth defects in timber, knots, cracks, slashes, burrs, and resin capsules are noteworthy, with most of these defects arising from the natural growth of trees. However, in the context of wood panel utilization, these are considered as wood defects. Knots, for example, are further classified into live knots (Fig. 1a) and dead knots (Fig. 1b).

This paper seeks to conduct a comprehensive examination of prior research on the physiological and psychological reactions triggered by wood defects, specifically knots. The objective is to ascertain whether overall wood utilization can be improved with a greater understanding of the beneficial aspects of all wood, including wood with defects.

Methodology

This study, inspired by Harzu C (Harzu, 2021), uses a systematic literature review to explore what has been studied about how people react both mentally and physically to wood defects. Literature reviews are essential for advancing different fields by enhancing concepts, methods, and themes. This review combines two approaches: one looking deeply into a specific field and another using a particular framework for analysis. To ensure a thorough and clear systematic review, the study follows a set of guidelines called the "Scientific Procedures and Rationales for Systematic Literature Reviews" (SPAR-4-SLR) protocol, outlined by Paul and colleagues in 2021 (Paul et al., 2021). This protocol ensures a rigorous, transparent, and systematic review process, divided into three main stages and six sub-stages, as shown in Figure 2.

1) **Assembling:**

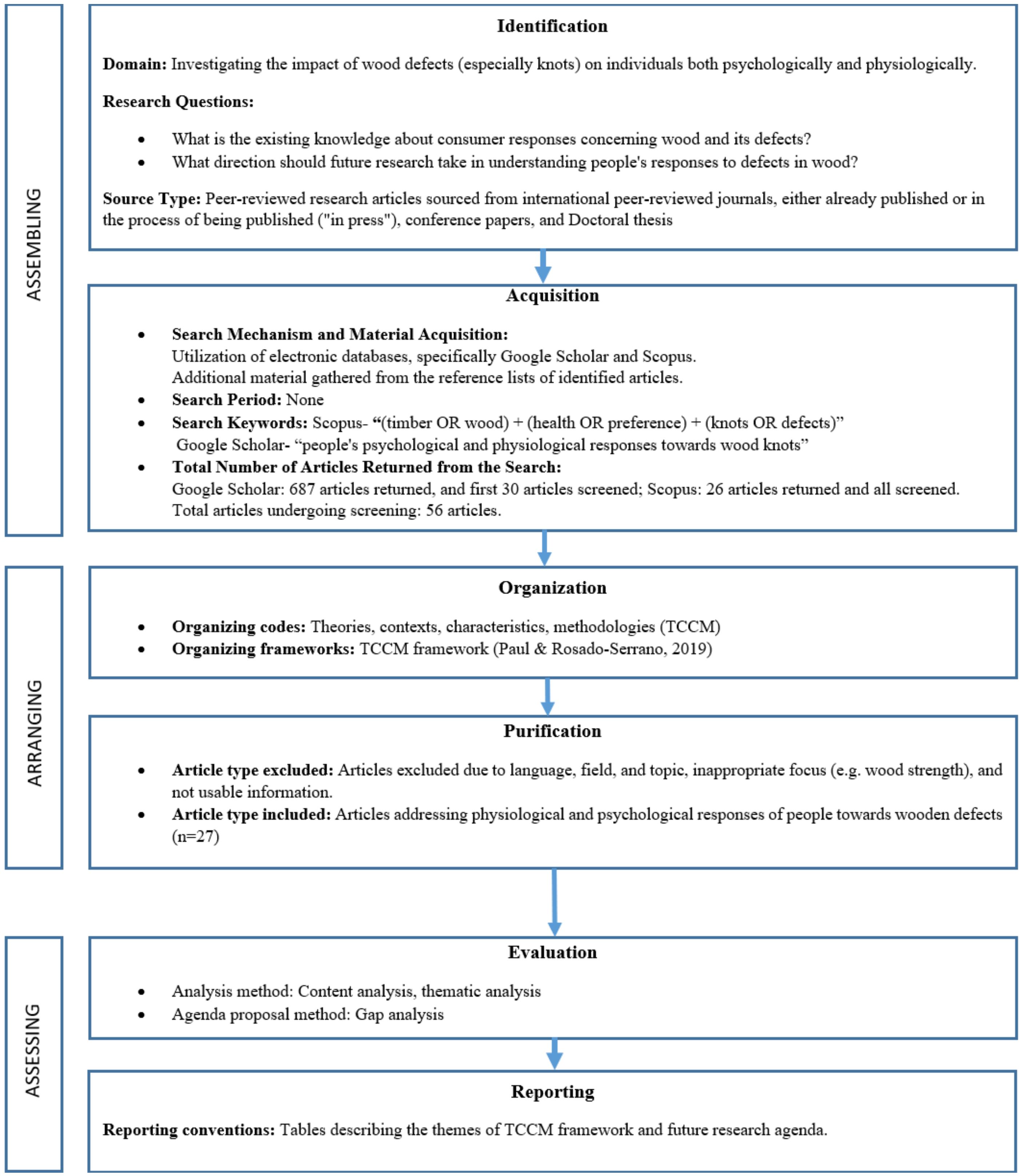
In the initial assembling stage, the focus is on identifying and gathering literature that has not been combined before, following the procedure outlined by Paul and colleagues in 2021 (Paul et al., 2021). During the identification sub-stage, essential elements like the domain, research questions and source type are specified. A detailed presentation of the domain and research questions guiding this review can be found in Figure 2. The study's material consists of peer-reviewed research articles, either already published or in the process of being published, obtained from international peer-reviewed journals.

In the acquisition phase, research articles either published or in an "in press" status are collected from two electronic databases, namely Scopus and Google Scholar. In Scopus, the search was conducted using the keywords "(timber OR wood) + (health OR preference) + (knots OR defects)," yielding 26 results.

Similarly, on Google Scholar, the search was performed using the phrase "people's psychological and physiological responses towards wood knots," with the filter set to select only articles. This search generated 687 results. Given the scarcity of research on this topic across different years, no specific range of years was chosen. The numerous research articles retrieved were then evaluated by reviewing their abstracts.

When sorting the results by relevance on Google Scholar, the initial pages contained the most pertinent research articles. However, as subsequent pages were explored, the relevance of the articles gradually diminished. Once the point of saturation was reached, indicating a diminishing return of relevant articles, the search for additional relevant articles was stopped.

Furthermore, the reference lists of systematically retrieved articles were examined for comprehensive coverage. Given the diverse nature of the research topic, spanning perspectives from forest sciences, consumer behavior, timber defects, physiology, and psychology, a broad scope was necessary to collect pertinent information from various scientific fields. 56 records undergo screening based on their publication titles and abstracts.



Figuure 2. Implementation of the systematic literature review according to the SPAR-4-SLR protocol (Paul et al., 2021)

2) Arranging

The second step of the SPAR-4-SLR protocol, known as "arranging," involves the systematic organization of literature using specific organizing codes and refining the material (Paul et al., 2021). In the refinement phase, studies from the original searches were incorporated into this systematic review if they met the predetermined inclusion criteria, which are elaborated below:

a) **Field and Topic**

The database searches were conducted to unveil how individuals physiologically and psychologically respond to wood defects, specifically emphasizing knots. Instead of investigating responses to wood in its entirety, the attention was narrowed down to reactions associated with specific wood characteristics, such as knots. As a result, the structural, mechanical, and other effects of wood defects were overlooked.

b) **Study Design**

Articles adopting conceptual/theoretical and empirical research designs, irrespective of their qualitative or quantitative nature, were included.

c) **Year of Publication**

The selection of the year range was omitted due to the restricted number of studies conducted on this specific topic.

d) **Language**

Only studies presented in the English language or languages translated to English were considered.

e) **Publication Status**

Peer-reviewed research articles, either published or in a state of "in press" in international peer-reviewed journals, were eligible for inclusion.

The refinement process comprised three consecutive steps. In Step 1, studies were screened based on publication titles to ensure alignment with inclusion criteria, including the field and topic. Studies outside the relevant field (e.g., agriculture) or focusing on other topics (e.g., concrete structure and its impact on people) were excluded. In Step 2, abstracts of selected studies were examined, and those deviating from the specific focus on wood defects, as well as studies related to the effects on physical and mechanical strength and properties of wood, were excluded. Techniques for knot detection were also excluded. Step 3 involved a detailed evaluation of potentially suitable studies against the inclusion criteria, resulting in the inclusion of 27 studies addressing physiological and psychological responses to wood defects, published across 10 journals. The literature reviewed predominantly originated from fields like forest sciences, environmental and sustainability studies, and wood sciences, with some studies from psychology and anthropology meeting the inclusion criteria.

3) **Assessing**

The last stage of assessing includes the evaluation and reporting of the reviewed literature (Paul et al., 2021).

Results

1) **Theory development**

This section presents all the articles included and analyzed in this literature review. Table 1 describes the scientific articles used in the literature review including the journals, titles, the article types are defined, and the research contexts and theoretical approaches. Each article is provided with an identification number.

Most of the included articles were empirical papers (26), while just one was theoretical. The articles investigated psychological responses (17), physiological responses (1), both psychological and physiological responses (5) and neither physiological nor psychological (4).

2) **Context**

The reviewed literature was published in 15 publications which are presented in Table 2.

Most of the studies are research articles (23), two are conference papers, one forest report and one doctoral thesis.

Table 3 presents the geographical context of the articles included in the literature review. It shows that most of the published research was conducted in Japan (11), Sweden (4), Norway (2), Canada (1), Sri Lanka (1) and Germany (1).

3) **Methodology**

Methodology (M) Table 4 demonstrates the different methodologies used in the analyzed literature. Based on the literature review results, most of the studies used quantitative (13) methodology followed by mixed methodology involving both quantitative and qualitative approaches (10) and three used qualitative methodology.

Characteristics

The characteristics of the reviewed articles refer to quality cues, quality attributes, and personal variables identified from the reviewed literature (Table 5 and 6).

Discussion

This section discusses the previous findings according to the TCCM framework (Paul & Rosado-Serrano, 2019) and presents the themes and sub-themes emerging from the reviewed literature. The TCCM framework stands for Theory, Context, Characteristics, and Methodology. This framework serves as an organizing structure for analyzing and evaluating content in systematic literature reviews, particularly in the context of research papers or studies.

1) **Theory Development:**

Impact of Wood Defects on Consumer Preferences

While smell and touch are crucial senses contributing to our preference for wood, most existing research focuses on visual responses, particularly surface features like texture, knots, color, and contrast (WOOD, 2022).

The wood industry predominantly employs sorting and classification procedures for solid wood in construction that concentrate on technical properties like strength, elasticity, and

Publications name	Types of papers (under review) published in these publications	Number of papers
Mokuzai Gakkaishi-Journal of Japan Wood Research Society	Research Articles	8
Journal of Wood Science –Journal of Japan Wood Research Society	Research Articles	4
Wood Science and Technology (2022)	Research Articles	2
Annals of Forest Science	Research Articles	2
Wood and Fiber Science	Research Article	1
Sustainability 2020	Research Article	1
Journal of Physiological Anthropology	Research Article	1
New Zealand Journal of Forestry Science	Research Article	1
European Journal of Wood and Wood Products	Research Article	1
Canadian Journal of Forest Research	Research Article	1
Bulletin of Kyoto University Forests	Forest Report	1
Nancy: INRA Editions, 1996. p. 343-352	Conference Paper	1
Luleå: Luleå tekniska universitet, 2000, p. 32	Doctoral Thesis	1
Virginia Tech, 2000.	Conference Paper	1
Forest Products Journal	Research Article	1

Table 2: Top journals for wood defects research

Geographical Context	Number of research papers
Japan	11
Sweden	4
Norway	2
Canada	1
Germany	1
Sri Lanka	1

Table 3: Geographical Focus of literature

Dimension	Variable	Type of variable	Examples	No. of studies
Sensory Dimension	Visual Properties	Intrinsic cues	Knots (Nakamura & Kondo, 1987), (Nakamura et al., 1993)	26
Social Dimension	Symbolic properties	Experience Attributes	Mental or physical relaxation	26

Table 5: Quality cues and attributes of wood

Variable		Type of variable	Examples	Number of studies
Personal Variables	Age	Socio-Demographic Variable	Women in 20s (Ikei et al., 2020)	2
	Gender	Socio-Demographic Variable	Female (Ikei et al., 2020)	1
	Nationality	Socio-Demographic Variable	Norway (Nyrud et al., 2008), Germany (Manuel et al., 2015)	25

Table 6: Personal variables identified from the reviewed literature.

dimensional stability(Manuel et al., 2015), (Kretschmann, 2010). This practice tends to favor 'clear' types of solid wood with higher grades, while structural deviations such as knots, grain orientation, and cracks are labeled as 'defects' and receive lower grades or face rejection. Unfortunately, this approach results in limited variety in finished wood products as technical defects like knots or cracks are minimized or absent, adhering to standards such as DIN EN 1611–1:2002–11. Significantly, this sorting approach overlooks optical surface parameters that could be crucial in attracting consumers.

Few studies have delved into the connection between the individual appearance of wood surfaces and consumer preferences. A study found a preference for wood surfaces with a homogeneous visual appearance(Høibø & Nyrud, 2010b), while another highlighted that diverging or mismatching wood features carry more weight in people's evaluations than the overall look of a wood surface (O. Broman, 1995). Other research indicates that subjective criteria such as being 'warm,' 'natural,' and 'harmonious' play a role in people's appreciation of wood (N. O. Broman, 1995).

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Research Topics	Publications	Type of Article	Research Context	References	Country
1. Influence of knots on psychological images of panels	Bulletin of Kyoto University Forests	Empirical	Psychological data	(Nakamura & Kondo, 1987)	Japan
2. Influence of knots and grooves on psychological images of wood wall panels	Mouza Gakkaishi-Journal of the Japan Wood Research Society	Empirical	Psychological data	(Nakamura et al., 1993)	Japan
3.Visual factors influencing psychological images of woods and stones	Mokuzai Gakkaishi-Journal of the Japan Wood Research Society	Empirical	Psychological data	(Nakamura et al., 1994)	Japan
4.Attitude toward Scots pine wood surfaces: a multivariate approach	Mokuzai Gakkaishi- Journal of Japan Wood Research Society	Empirical	Psychological data	(O. Broman, 1995)	Japan
5.Visual impressions of features in Scots pine wood surfaces: A qualitative study	Forest Products Journal	Empirical	Psychological data	(N. O. Broman, 1995)	N/A
6. Two methods for measuring people's preferences for Scots pine wood surfaces: a comparative multivariate analysis.	Mokuzai Gakkaishi- Journal of Japan Wood Research Society	Empirical	Psychological data	(O. Broman, 1996)	Sweden
7. Description of visual characteristics of wood influencing some psychological images	Mokuzai Gakkaishi-Journal of Japan Wood Research Society	Empirical	Psychological data	(NAKAMURA et al., 1996)	Japan
8. The end-users' requirements for the aesthetical features of Scots pine wood	Nancy: INRA Editions, 1996. p. 343-352	Empirical	Psychological data	(O. Broman & Grönlund, 1996)	N/A
9. Means to Measure the Aesthetic Properties of Wood	Luleå: Luleå tekniska universitet, 2000., p. 32	Empirical	Psychological data	(O. Broman, 2000a)	Sweden
10. The measurement of wood features in knotty Scots pine wood surfaces and the connection with people's preferences.	Virginia Tech, 2000.	Empirical	Psychological data	(O. Broman, 2000b)	Sweden
11. Aesthetic properties in knotty wood surfaces and their connection with people's preferences	Journal of Wood Science- Journal of Japan Wood Research Society	Empirical	Psychological data	(N. O. Broman, 2001b)	Sweden
12. Influence of wood wall panels on physiological and psychological responses	Journal of Wood Science- Journal of Japan Wood Research Society	Empirical	Physiological + Psychological data	(Sakuragawa et al., 2005)	Japan
13. Two complementary indicators to rank various oak wood defects according to different users' advice	New Zealand Journal of Forestry Science	Empirical	None	(Cavaignac et al., 2006)	N/A
14. Appearance wood products and psychological well-being	Wood and Fiber Science	Empirical	Psychological data	(Rice et al., 2006)	Canada
15. Characterization of distribution pattern of eye fixation pauses in observation of knotty wood panel images	Journal of Physiological Anthropology	Empirical	Physiological data	(Nakamura & Kondo, 2007)	N/A
16. Product attributes affecting consumer preference for residential deck materials	Canadian Journal of Forest Research	Empirical	Psychological data	(Nyrud et al., 2008)	Norway
17. Quantification of visual inducement of knots by eye-tracking	Journal of Wood Science-Journal of Japan Wood Research Society	Empirical	Psychological + Physiological data	(Nakamura & Kondo, 2008)	N/A
18. Consumer perception of wood surfaces: the relationship between stated preferences and visual homogeneity	Journal of Wood Science- Journal of Japan Wood Research Society	Empirical	None	(Høibø & Nyrud, 2010a)	Norway
19. Consumers' perceptions and preference profiles for wood surfaces tested with pairwise comparison in Germany	Annals of Forest Science	Empirical	Psychological data	(Manuel et al., 2015)	Germany
20. Effect of observation of wooden-wall panels on eye fixation related potentials, eye movement and sensory evaluation	Mokuzai Gakkaishi-Journal of Japan Wood Research Society	Empirical	Physiological + Psychological data	(Yoshida et al., 2016)	Japan
21. Preference evaluation based on cognitive psychology of the quantity of knots present in wood wall panels II –Effects of ratio of knot area of todomatsu wall panels and setting on people's preference	Mokuzai Gakkaishi - Journal of Japan Wood Research Society	Empirical	Psychological data	(Matsumoto et al., 2016a)	Japan
22. Preference evaluation based on cognitive psychology of the quantity of knots present in wood wall panels I –Effects of the ratio of knot area of todomatsu wall panels and of room type on people's preferences for residential living rooms	Mokuzai Gakkaishi- Journal of Japan Wood Research Society	Empirical	Psychological data	(Matsumoto et al., 2016b)	Japan
23.The effect of quality attributes in determination of price for plantation-grown teak (Tectona grandis) logs in Sri Lanka	Annals of Forest Research	Empirical	None	(Jayawardhane et al., 2016)	Sri Lanka
24. Visual and visuo-tactile preferences of Malagasy consumers for machined wood surfaces for furniture: acceptability thresholds for surface parameters	European Journal of Wood and Wood Products	Empirical	Psychological data	(Ramanakoto et al., 2017)	N/A
25. Physiological effects of visual stimulation using knotty and clear wood images among young women	Sustainability 2020	Empirical	Physiological + Physiological Data	(Ikei et al., 2020)	Japan
26. Effects of visual stimulation using wooden-wall images with different amounts of knots on psychological and physiological responses	Wood Science and Technology (2022)	Empirical	Psychological +Physiological Data	(Nakamura et al., 2022a)	Japan
27. The Nature of Wood: An Exploration of the Science on Biophilic Responses To Wood	Wood Science and Technology (2022)	Theoretical	None	(WOOD, 2022)	N/A

Table 1: List of scientific articles used in literature review

References	Methodology
(Nakamura & Kondo, 1987)	Mixed -Qualitative: Questionnaires; -Quantitative: Data Analysis Methods and Results
(Nakamura et al., 1993)	Qualitative: Questionnaires
(Nakamura et al., 1994)	Qualitative: Questionnaires
(O. Broman, 1995)	Quantitative : correlation analysis, principal component analysis, and partial least squares analysis
(N. O. Broman, 1995)	Qualitative: Interviews
(O. Broman, 1996)	Quantitative: Structured data collection and Statistical analysis
(NAKAMURA et al., 1996)	Quantitative: Image analysis techniques
(O. Broman & Grönlund, 1996)	Mixed -Qualitative - Quantitative: Statistical models
(O. Broman, 2000a)	Mixed -Qualitative: Interviews and Qualitative analysis -Quantitative: Projection methods such as Principal Component Analysis (PCA) and Partial Least Squares (PLS)
(O. Broman, 2000b)	Mixed Qualitative: Qualitative analysis Quantitative: Statistical analysis, specifically Partial Least Squares (PLS) analysis
(N. O. Broman, 2001b)	Mixed -Qualitative: Qualitative Assessments -Quantitative: Principal Component Analysis (PCA)
(Sakuragawa et al., 2005)	Quantitative: Statistical analyses, continuous blood pressure measurements, Semantic differential method and the Profile of Mood States test
(Cavaignac et al., 2006)	Mixed -Qualitative -Quantitative: Analysis of price data
(Rice et al., 2006)	Mixed -Quantitative: Self-administered survey -Qualitative: Interviews and Q-sort exercise
(Nakamura & Kondo, 2007)	Quantitative: Numerical indexes
(Nyrud et al., 2008)	Mixed -Qualitative and Quantitative: Sensory Analysis
(Nakamura & Kondo, 2008)	Quantitative: Eye-tracking data analysis, numerical indexing of pausing probability, correlation analysis, and sensory evaluation with numerical scales
(Høibø & Nyrud, 2010a)	Quantitative: Visual variables
(Manuel et al., 2015)	Quantitative: Multidimensional scaling and latent class analysis
(Yoshida et al., 2016)	Mixed -Qualitative: Sensory evaluation -Quantitative: Eye tracking, Electroencephalography (EEG)
(Matsumoto et al., 2016a)	Quantitative: Analysis with analysis of variance (ANOVA)
(Matsumoto et al., 2016b)	Quantitative: Analysis with analysis of variance (ANOVA)
(Jayawardhane et al., 2016)	Quantitative: Statistical techniques, multiple linear regression
(Ramanakoto et al., 2017)	Mixed -Qualitative : qualitative assessments such as visual and visuo-tactile tests -Quantitative: Statistical analysis
(Ikei et al., 2020)	Quantitative
(Nakamura et al., 2022a)	Quantitative

Table 4: Methodology based clustering of literature.

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Individuals' aesthetic preferences for wood are rooted in two primary visual dimensions: texture and color, with the frequency of knots on the surface influencing preferences to some extent (Dai et al., 2023).

Another study underscored the importance of surface properties of wood, particularly in terms of the psychological sensations of wood users (Sadoh & Nakato, 1987).

In a comprehensive classification of floorboards, including knotty floors, distinct preference profiles among seven consumer groups for various floor images was revealed (Manuel et al., 2015). Similarly, other studies (Matsumoto et al., 2016a) (Matsumoto et al., 2016b) highlighted the pivotal role of knot quantity in wooden wall panels in preference evaluations for diverse room types, such as residential living rooms, restaurants, and hotel receptions.

When buying teak logs, customers assess their quality by visual appraisal of surface characteristics such as visible defects (Jayawardhane et al., 2016). Hence, the buyers' preference for logs with desired attributes is reflected by the price achieved in the market. The presence of high number of knots had the highest detrimental impact on price, followed by the higher bend fraction, presence of hollows at top end and/or middle of the log, presence of heart rot and presence of buttresses respectively.

Touch allowed better appreciation of surface defects than a simple visual observation (Ramanakoto et al., 2017). Consumers like smooth surfaces without visible defects and less visible peaks of waviness.

The collective body of research underscores that knots are visually undesirable attributes in wood, with repercussions on preference and the commercial value of wood products.

Influence of Wood Defects: Knots on Human Psychology

Knots emerge as a distinctive surface feature in wood, originating from the remnants of branches within the tree trunk (Nakamura et al., 2022a). The growth of new wood layers over the existing ones during seasonal growth embeds branch bases more deeply in the trunk as the main stem diameter expands (Shmulsky & Jones, 2019). Despite indicating that the wood originated from a living tree, knots are deemed undesirable surface defects, significantly compromising both the mechanical and aesthetic qualities of lumber.

A limited number of knots on the surface pattern of wood has been the subject of several studies, indicating a preference for wood with fewer knots (WOOD, 2022). Survey findings suggest that a few knots are intriguing, while an abundance of knots is generally disliked. Eye-tracking systems, which monitor the movement of the eyes across an image and record pauses at specific points, reveal that wood with numerous knots tends to elicit more frequent pauses. This observation suggests that more cognitive effort may be required to process what is being viewed. Researchers also observed that the presence of parallel, colored grooves diverted attention away from the knots. This leads us to question whether the calming and preference responses are primarily influenced by the inherent nature of the wood grain itself.

Exploration into the psychological responses to visual stimuli from knotty wooden images or products has revealed noteworthy findings. Knotty wall panels evoke natural impressions (Nakamura & Kondo, 1987), but the agreeable impressions diminish as the number of knots increases (Nakamura & Kondo, 1987) (Nakamura et al., 1993).

Some studies found a preference among consumers in Northern Europe for clear surfaces over knotty ones(N. O. Broman, 1995; O. Broman, 1995, 1996). The selection of knotty surfaces hinges on achieving a delicate balance between visual harmony and activity (N. O. Broman, 2001b). There is a significance of a homogeneous appearance and medium color strength in consumer preferences for knotty wood deck products (Nyrud et al., 2008). Similarly, a study underscored the experimental link between surface homogeneity and preferred wood products, an association significantly influenced by the presence of knots (Høibø & Nyrud, 2010b).

Influence of Wood Defects: Knots on Human Physiology

Limited studies have experimentally delved into the physiological impact of knots on wood surfaces as visual stimuli for humans(Nakamura et al., 2022b). A study employed two full-sized wall panels—a knotty hinoki (Japanese cypress) wall and a plain white steel wall—to compare the physiological and psychological responses evoked by visual stimulation. The results demonstrated that visual stimulation using the knotty hinoki wall panel significantly reduced blood pressure among participants who favored the knotty wall panel, with no significant increase in blood pressure among those who did not favor it (Sakuragawa et al., 2005).

Other studies employed eye-tracking techniques to explore the impact of knots, revealing a robust linear correlation between the probability of fixations on knots and their subjective noticeability (Nakamura & Kondo, 2007, 2008). However, their assessments were confined to eye movements and sensory evaluations of participants viewing full-sized knotty wall images. Similarly, in other studies, assessments of eye fixation-related potentials, eye movements, and sensory evaluations were conducted among participants viewing full-sized wooden-wall images, including a knotty wall, aiming to evaluate the effects of basic design attributes of wooden-wall panels. While cognitive responses varied due to visible characteristics, the specific impact of knots on cognitive responses remained unclear (Nakamura et al., 2022a; Yoshida et al., 2016).

Some specific studies seem to play a crucial role in establishing whether the dislike of knots is an inherent physiological reaction or a learned preference. A study (Ikei et al., 2020) evaluated the physiological effect of knotty images as visual stimuli, employing well-prepared full-scale knotty and clear wooden wall images. Oxyhemoglobin concentration (oxy-Hb) in the left and right prefrontal cortex, an indicator of brain activity, and heart rate variability (HRV), an indicator of autonomic nervous activity, were assessed. Results indicated that the knotty wooden-wall image decreased right prefrontal cortex activity compared to the control (gray image), and clear wooden-wall images reduced left prefrontal cortex activity. However, there was no significant difference in the physiological indices between the effects of knotty and clear wooden-wall images. Despite negative psychological effects associated with knots, confirmation of similar negative physiological effects is yet to be established.

In the experiment (Ikei et al., 2020) assessing physiological responses induced by knots, it was observed that both knotty and clear wooden-wall images significantly reduced prefrontal cortex activities compared to the gray image. The knotty wooden-wall image significantly increased parasympathetic nerve activity, while the clear wooden-wall image significantly reduced sympathetic nerve activity. However, the hypothesis that there is a difference in physiological responses between participants observing wooden-wall images without knots and those observing images with knots could not be clearly confirmed due to the limited availability of wooden-wall images with knots.

Following the completion of this experiment, another study (Nakamura et al., 2022a) was carried out to evaluate the physiological and psychological impacts of knots on individuals. In this investigation, the wooden-wall image featuring a limited number of knots, akin to the clear wooden wall image, produced comparable effects on psychological responses. Furthermore, the wooden-wall image with numerous knots significantly diminished psychological benefits when compared to the clear wooden-wall image. However, the presence or absence of knots and the quantity of knots did not yield significant effects on oxy-Hb concentrations in the left and right prefrontal cortex and HRV. Consequently, the physiological effects induced by knotty woods were not substantiated.

2) Context:

The research context, as revealed through a literature review of various past research papers, centers around an investigation into the physiological and psychological responses of individuals to wood, with a specific emphasis on wood defects, particularly knots. The primary objective is to understand how people react both physically and mentally to specific features of wood, particularly knots, and how these responses may influence preferences and well-being.

Most of the studies within this research context are empirical, meaning they involve direct observation, experimentation, or measurement to gather data. These empirical studies extensively explore the psychological responses of individuals, seeking to understand how people perceive and emotionally react to various aspects of wood, with a particular focus on the presence of knots.

In addition to psychological responses, some studies within this context also investigate physiological responses. These studies use various methods, including eye-tracking technology, to measure eye movements, fixation pauses, and other physiological indicators. The goal is to gain insights into the impact of wood on human physiology and attention patterns related to wood surfaces.

Consumer behavior is a recurring theme in this research context, with several studies examining how individuals perceive and prefer wood products. Factors such as aesthetics, visual impressions, and the quantity of knots are considered in understanding consumer preferences for wood surfaces.

Cognitive psychology is another dimension explored in certain studies, examining how cognitive processes influence the evaluation and preference for wood surfaces. The research extends into environmental psychology, studying the impact of wood on psychological well-being and the overall perception of wooden environments.

Eye-tracking technology is utilized in certain studies to measure eye movements and fixation pauses, providing insights into visual inducement and attention patterns related to wood surfaces. The exploration of biophilic responses to wood is a recurring theme, reflecting the connection between humans and nature, particularly in the context of wood as a natural material.

The research context also includes one theoretical study (WOOD, 2022). This theoretical study provides a conceptual framework or theoretical insights into biophilic responses, contributing to the overall understanding of how humans interact with wood.

In summary, the research context suggests a multidisciplinary approach that incorporates aspects of psychology, physiology, consumer behavior, and environmental psychology to comprehensively understand how people respond to wood, especially concerning defects like knots. The collective body of studies contributes to a nuanced understanding of the psychological and physiological aspects of the human-wood interaction.

3) Characteristics

The characteristic section weaves together quality cues, attributes, and personal variables, offering a nuanced understanding of the sensory and social dimensions of individuals' responses to wood defects. The focus on knots as a central quality cue, coupled with the exploration of symbolic properties and socio-demographic factors, provides a comprehensive foundation for understanding the intricate nuances in how people perceive and react to wood, particularly in the context of defects. This thorough exploration sets the stage for future research directions and contributes to a holistic understanding of the human-wood interaction.

4) Methodology

The methodologies employed across the referenced studies demonstrate a diverse range of approaches used to investigate various aspects related to wood products and their impact on human perception and behavior. These methodologies encompass both qualitative and quantitative techniques, reflecting the multifaceted nature of research in this field.

Qualitative methodologies, such as questionnaires, interviews, and qualitative analysis, were frequently utilized to explore subjective aspects of participants' experiences and perceptions (Nakamura & Kondo, 1987) (Nakamura et al., 1993) (Nakamura et al., 1994) (N. O. Broman, 1995) (O. Broman, 2000a; O. Broman & Grönlund, 1996) (O. Broman, 2000b) (N. O. Broman, 2001b) (Rice et al., 2006) (Yoshida et al., 2016) (Ramanakoto et al., 2017). These approaches offer rich insights into the nuanced aspects of human preferences and responses to wood surfaces, allowing researchers to uncover underlying motivations and attitudes towards different wood products.

On the other hand, quantitative methodologies played a crucial role in many studies, providing objective measures and statistical analyses to quantify relationships and patterns observed in the data (O. Broman, 1995) (O. Broman, 1996) (NAKAMURA et al., 1996) (Sakuragawa et al., 2005) (Cavaignac et al., 2006) (Nakamura & Kondo, 2007) (Nakamura & Kondo, 2008) (Høibø & Nyrud, 2010a) (Manuel et al., 2015) (Matsumoto et al., 2016a) (Matsumoto et al., 2016b) (Jayawardhane et al., 2016) (Ikei et al., 2020) (Nakamura et al., 2022a). Techniques such as correlation analysis, principal component analysis (PCA), partial least squares (PLS) analysis, and analysis of variance (ANOVA)

were commonly employed to analyze numerical data and identify significant associations between variables.

Several studies adopted mixed-method approaches, combining both qualitative and quantitative techniques to gain a comprehensive understanding of the research questions at hand (O. Broman, 2000a) (O. Broman, 2000b) (Nyrud et al., 2008) (Yoshida et al., 2016) (Ramanakoto et al., 2017). By integrating diverse methods, researchers were able to triangulate findings, validate results, and offer more robust interpretations of their findings.

One notable trend observed across the studies is the utilization of advanced technologies, such as eye-tracking, electroencephalography (EEG), and image analysis techniques (NAKAMURA et al., 1996) (Sakuragawa et al., 2005) (Nakamura & Kondo, 2008) (Yoshida et al., 2016). These innovative approaches allowed researchers to capture real-time physiological responses and objective visual data, providing valuable insights into the neurological and perceptual mechanisms underlying human interactions with wood surfaces.

Overall, the methodologies employed in the referenced studies underscore the interdisciplinary nature of research in wood science and human perception. By combining insights from psychology, sensory analysis, and statistical modeling, researchers can inform the design, marketing, and production of wood products that align with consumer preferences and contribute to the creation of aesthetically pleasing and functional living environments. However, further research is warranted to explore the complex interplay between wood attributes, human perception, and environmental contexts, paving the way for future advancements in this field.

Thematic area	Suggested topics derived from recognized gaps in research
Theory Development	• Methods to accurately measure the psychological reactions of individuals to wood defects
Context	• Examination of the variations in responses exhibited by individuals from various global regions, encompassing diverse cultural backgrounds
Characteristics	• Investigation into the correlation between socio-demographic characteristics of individuals and their responses to wood defects
Methodology	• Examination of how people's responses to wood defects evolve over time

Table 7: Proposed topics for future research

Gaps in the Currently Examined Literature and Prospectuis for Future Reserch

The identified gaps in the existing literature pave the way for potential areas of exploration in future research. Proposals for advancing theory development, exploring diverse contexts, investigating distinct characteristics, and refining methodologies are outlined in Table 7, aligning with the TCCM framework (Paul & Rosado-Serrano, 2019). This table serves as a guide for a future research agenda, highlighting key themes for further investigation.

Following an extensive analysis of existing literature, it became evident that, despite numerous studies conducted across different countries, none of the individual research endeavors encompassed participants from diverse countries or backgrounds within the same study. Consequently, there is a necessity to investigate the variations in responses displayed by individuals from different global regions. Moreover, a limited number of studies, concentrated on socio-demographic factors like gender (Ikei et al., 2020). However, additional research is imperative to explore whether individual responses differ based on socio-demographic characteristics such as gender, age, and other pertinent factors. Notably, all the conducted research focused on present responses, yet there is an absence of investigations into whether individuals acclimate to defects over time and how their responses may undergo transformations across different timeframes. This underscores the need to delve into the longitudinal aspect of responses to wood defects and their evolving nature over time.

Conclusion

Incorporating timber as a biophilic design element has been shown to alleviate stress and improve comfort levels, highlighting MTC's potential to positively impact various aspects of the indoor environment.(Whyte et al., 2024). These previous studies have focused on higher grade timber without defects. This systematic literature review provides a comprehensive overview of research conducted on the physiological and psychological responses of individuals to wood characteristics i.e. wood defects, with a specific emphasis on knots. Employing the SPAR-4-SLR protocol (Paul et al., 2021), the study assembled, arranged, and assessed literature from diverse fields such as forest sciences, consumer behavior, timber defects, physiology, and psychology.

The analysis, guided by the TCCM framework (Paul & Rosado-Serrano, 2019) reveals valuable insights into the impact of wood defects on human experiences, preferences, and well-being.

The results indicate a predominant focus on empirical studies, with a specific interest in understanding consumer preferences, cognitive responses, and physiological reactions to wood, particularly knots. The reviewed literature spans diverse contexts, including wood panels, surfaces, building materials, and certified wood products. Geographically, studies were conducted in various countries, emphasizing a global perspective on the topic.

Methodologically, the research exhibits a broad spectrum, incorporating qualitative/quantitative methods like questionnaires, interviews, and statistical models, along with sophisticated quantitative approaches such as eye-tracking technology. The evolution of methodologies over time reflects a growing emphasis on capturing both the depth and breadth of individuals' responses to wood defects.

The discussion synthesizes findings according to the TCCM framework, highlighting the interplay of Theory, Context, Characteristics, and Methodology. It uncovers the theoretical foundations underpinning wood preferences, explores the diverse contexts in which studies were conducted, and delves into the characteristics of wood defects, particularly knots. The integration of both physiological and psychological dimensions provides a holistic understanding of the human-wood interaction.

Research gaps underscore the necessity for further investigation into wood defects across diverse cultural, socio-demographic, and temporal dimensions.

List of Abbreviations

MTC: Mass Timber Construction
EDA: Electro Dermal Activity
HRV: Heart Rate Variability
Oxy-Hb: Oxyhemoglobin concentration
PASAT: Paced Auditory Serial-Addition Task
SPAR-4-SLR: Scientific Procedures and Rationales for Systematic Literature Reviews
TCCM: Theories, contexts, characteristics, methodologies

Declarations

Availability of data and materials
Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

The authors confirm contribution to the paper as follows:
Study conception and design: Crovella, Chapagain
Data collection: Chapagain
Analysis and interpretation of results: Chapagain
Draft manuscript preparation: Chapagain, Crovella
All authors reviewed the results and approved the final version of the manuscript.

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