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Towards a new understanding: building a shared mental model for design teams

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ABSTRACT: Understanding how Shared Mental Models (SMMs) develop within design teams has sparked interest in the design community of decades. But to date, there is still a lack of understanding of the factors that influence the development of these structures. This review examines the literature related to SMMs and the factors that impact collaborative efforts. Aiming to bring these two research fields together, this review proposes a new framework to help researchers better understand how SMMs develop and provide a foundation for new research and empirical evidence to establish the factors that influence the development of SMMs

KEYWORDS: design cognition, collaborative design, design theory

1. Introduction

Mental Models are internal representations of the world that influence our behaviours, thoughts, and actions. Mental Models are a concept that is acknowledged in psychology and cognitive science since 1943 (Jones et al., 2011). This concept is widely recognised in design collaboration and design cognition research (Badke-Schaub et al., 2007; Casakin & Badke-Schaub, 2017; Gero & Kan, 2007). Whilst there has been considerable effort to understand Shared Mental Models (SMMs) within engineering design, the question of how or when SMMs develop within design teams has limited exploration. This research aims to fill a gap in knowledge by establishing a foundation for further research, contributing a deeper understanding of how SMMs develop during collaborative design efforts and presents a new framework, following a process theory approach that can rely on qualitative data to be empirically proven (Wegner & Cash, 2020). The framework has been developed from the systematic review presenting potential factors that may impact the development of a SMM.
SMMs are also referred to as Team Mental Model's within the research literature, to ensure consistency throughout this paper, we refer to Team Mental Models as Shared Mental Models.

2. Methodology

In this section, the criteria and process for the systematic literature review and supplementary review is explained. The review was first developed to understand the individuals involved within design teams, later highlighting a more focused approach into the topic of SMMs. The first review was conducted in March 2024 with the supplementary review conducted in July 2024.
Four academic databases were used to obtain relevant articles: Scopus, Web of Science, The Design Society Library and Engineering Village. A search string was created using OR and AND Boolean operations. The final search was:
Attributes OR Characteristics OR Trait OR Qualit* AND Individual OR Team* OR Collaboration OR Group* AND Engineering OR Design.*
The search was refined to the titles, abstracts and keywords of articles. No date restrictions were applied to the search.

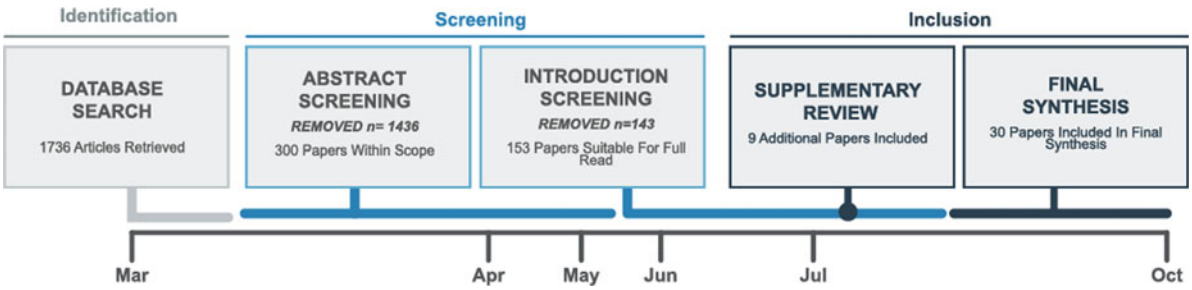

Figure 1. Flow diagram of research method

1736 relevant articles were returned from the database search. Full papers were downloaded and stored in a reference manager for exclusions. The first exclusion was to remove 71 duplicates.
Articles were screened based on titles and abstracts, 1436 papers were removed for meeting one of the two exclusion criteria: *EC1 not studying humans within teams, and/or EC2 not studying collaborative efforts.* The remaining paper (n=300) introductions were screened and papers that met exclusion criteria three: *EC3 did not include attributes / characteristics of collaboration or individuals*, were removed (n=147). The remaining papers (n=153) followed an inductive coding approach by the first author to identify relationships and key themes.
The systematic review presented a focused approach on SMM research within engineering design A supplementary review was then necessary to capture papers on the topic of SMM development in the field of design that were not captured in the initial search. The following search string was created: *'Mental model' and 'design'.*
Engineering was not included in this search as it restricted the papers available within the scope of this research. Nine additional papers from the supplementary review were included in the final synthesis of the review. The methodology for this review is shown in more detail in Figure 1.

3. Shared mental models

Shared Mental Models are knowledge structures that help a team: develop a shared understanding of the task, anticipate challenges, effectively coordinate actions, and adapt their behaviours to align with the requirements of the task and the dynamics of their teammates (Borrego et al., 2013). It can be argued that SMMs are a form of transactive memory (Wegner et al., 1991) as they too are knowledge structures, agreeing with the early research on mental models in cognitive science (Garnham & Oakhill, 1996). However, design research has narrowed the definition. Research by Badke-Schaub et al. (2007) has demonstrated that SMMs encompass more than just memory, but also our needs, experience, and active perception, aligning with situated cognition (Gero & Kulinski, 2006). We argue that SMM's fits in between these two forms of cognition.

3.1. Measuring shared mental models in design

Research over that past two decades has introduced multiple methods of capturing and measuring the sharedness of SMMs. Badke-Schaub et al. (2007) present a comprehensive overview of SMMs and ways of effectively measuring them such as concept mapping and observational analysis, providing a foundation for further research and larger what this work is building upon.
Casakin & Badke-Schaub, (2017) use protocol analysis to understand how SMMs develops over time, their outcome provides some observations but no definitive answers, so the question is how do SMMs develop?
Zeiler (2017) presents a method of measuring mental models using morphological charts. This allows designers to identify their own perceptions and make comparisons between other designer's perceptions. State it does not effectively measure the accuracy of a SMM, an issue highlighted by Schaub (2014). Yamada et al., (2015) presents a novel way of determining the development of a SMM overtime using a mathematical formula, however the case study used is of a simplistic brief, and therefore it is questionable if the outcomes accurately measure SMM's when design teams are tackling wicked problems. Research into SMMs within the domain of engineering design is argued to still be in an exploratory stage, due to the lack of established methods of accurately measuring them when design

teams are engaged in the design process (Dong et al., 2013). Whilst this argument has merit and justification as research in cognitive science states that mental models are hypothetical structures that cannot be directly observed (Johnson-laird, 1983) and cannot be accurately measured. In this paper, we argue that it is not because we do not have robust methods, but a lack of understanding on how SMMs develop during the design process.

3.2. The development of shared mental models

Badke-Schaub et al (2007) presents a framework for understanding how SMMs within engineering design. Their framework tells us that a team member will contextualise a situation based on their perceptions, experiences and knowledge which will create their individual mental model. They will share these mental models with other members within their team to create a SMM. This SMM can focus on five key aspects: the task, the process, the team, individual competence, or the context. These aspects, along with individual expectations based on members' skills and abilities, significantly impact team performance.

Schaub, (2014) has established some ways of ensuring a mental model develops within a design team. These examples are developing and establishing shared goals early in the project – backed by research by Yap et al (2020). Schaub (2014) states that designers need to reflect and seek feedback on their activities throughout the process as this ensures that the mental model stays relevant but does not elaborate on the ways in which to obtain this feedback and reflection, revealing a gap in knowledge. Finally, Schaub states that designers should embrace the mistakes and failures within their project and use these to adapt their mental model accordingly.

Gero and Kan (2009) imply that when SMMs develop, communication will decrease within a team setting. Though as Borrego et al (2013) suggest, SMMs develop when team members communicate their thoughts, therefore we argue the influence of communication on SMMs is unclear.

The highlighted papers above, demonstrates that design research still lacks an understanding on how SMMs develop within design teams. This research aims to understand this further by mapping Micro, Meso and Macro factors impact, building upon the definitions by Maier and Cash (2022). Micro factors are defined as anything that an individual brings to collaborative efforts, anything that the team does to impact collaborative efforts is a Meso factor, and finally any influence from the wider society brings to a collaborative effort is a Macro factor.

4. Factors affecting collaboration

4.1. Micro factors

Three Micro factors are believed to influence the development of SMMs: experience, motivation and levels of engagement. Badke-Schaub et al., (2007) states that experiences shape the development of a SMMs, however, does not elaborate on the specific experiences.

Schepers et al (2019) explored motivation between individuals and teams, stating that an individual's personality will shape their motivation. They go onto reveal that individuals have higher motivation during a design project when the team has more shared knowledge, and individuals will use their motivation from this to establish their level of engagement within the project. This is also found by Jiang et al (2022), who details the level of engagement an individual will subscribe to a project, they provide a set number of projects that impacts an individual's level of engagement; individuals will have high motivation and involvement when subscribed to less than six projects, medium levels of motivation and engagement when contributing to less than twelve and low levels of motivation and engagement when subscribed to more than twelve projects. Although this is a quantifiable number, they do not highlight what high, medium, and low levels of motivation or engagement are. Borrego et al (2013) also explores the different reasons for engagement in design teams, they talk about a designer's motivation and how this impacts their level of engagement. They state that when a project is not significantly complex enough, designers would lose interest and not engage in the project, therefore we propose that alongside the proposal in Section 3, that motivation, experience, and levels of engagement influence the development of a SMM. The extent to which it influences is still unknown.

4.2. Macro factors

In this review, three key Macro factors were identified. These factors being organisation, leadership, and prior social experience. Maier et al (2021) highlighted that organisations impact on communication practices within teams, they primarily emphasis that availability of information can impact upon the team and cause a lack of communication, the information comes from the organisation therefore it can conclude that organisations impact upon communicative practices. Further supported by Schnetler et al (2015) who states that organisational structures such as hierarchical, impact upon communication behaviours as information reporting can be confusing to team members and that these organisational structures often have issues relating to authority and responsibility of individuals, leading to power struggles and eventually causing conflict within teams. Therefore, we propose that macro factors influence the development of a SMM.

Leadership has been coded as a Macro factor as we refer to leaders that are not directly involved with the team, i.e. managers. Leadership has been reported to impact upon team dynamics (Zaman et al, 2023) and communication (Badke-Schaub & Hofinger, 2018). Zaman et al (2023) reports on the effectiveness of leaders in teams, primarily focusing on the negative side of leadership such as 'toxic' behaviours. These behaviours result in unsupportive leadership which will negatively impact on communicative practices within the team and leading to a skewed team dynamic, on the other end of the scale Badke-Schaub & Hofinger (2018) explores the positive behaviours of leadership. Highlighting that when a leader is effective, they encourage and promote communication between individuals. These effective leaders are also able to influence and mitigate conflict within teams and provide a more fruitful and enriching team dynamic for all parties involved.

In this research, prior social experience is coded as a Macro factor, as these are relationships that have existed outside of a professional setting and have a more societal relationship. Having prior experience with an individual has shown to allow for an established level of trust to exist – whether high levels or low levels of trust. Lykourentzou et al (2017) studied prior social relationships in the form of 'team dating' where different individuals work one on one with each other for a brief period and then build a team based off the results of the working relationship. Their study found that when individuals were more likely to select individuals they worked with even when better work quality was produced from individuals they did not work with, highlighting a that prior social experience within an individual is a foundation for trust. Supported by studies done by Singh et al (2022) and Tessier (2021) and, is mentioned by Nguyen and Mougenot (2022) and, Yap et al (2020). Badke-Schaub et al, (2007) does state that teams need to gain trust to develop a SMM, therefore we can say that a prior social experience between team members will influence the development of a SMM.

4.3. Meso factors

Throughout the review, seven meso factors have been identified to potentially influence the development of a SMMs within design teams, these being communication, conflict, trust, team dynamic, shared understanding, shared knowledge, and shared goals.

4.3.1. Communication and conflict

Communication is the act of sharing information between individuals. Communication can be done in various forms such as spoken, written, illustrated and gestures. Conflict is the act of disagreement within and outside groups, conflict can take many forms such as verbal, omission of information, psychological and, avoidance - whether of task or different actors within the process.

Communication is one of the core factors that impact on collaborative practices (Nguyen & Mougenot, 2022; Singh et al, 2019). Communication influences a number of other factors that affect collaborative practices such as trust (Nguyen & Mougenot, 2022; Schnetler et al, 2015), shared understanding (Cash et al, 2020; Kunrath et al, 2020; Maier et al, 2021), motivation and shared goals (Maier et al, 2021).

Communication has received significant attention over the years with each author expanding and adding to what affects communication. Alternatively, conflict has been an outcome of communication research. Communication is influenced by two aspects as found in literature: Organisation and Leadership. These Macro factors influence communication between actors as stated by Badke-Schaub & Hofinger (2018), Maier et al (2021), Schnetler et al (2015) and Zaman et al (2023).

Researchers such as Badke-Schaub and Hofinger (2018) propose what makes an effective team, highlighting communication impacts on a team's dynamic through support, and developing shared goals. From the perspective of Meso factors, Communication impacts on six out of seven identified factors that affect collaboration as displayed in Figure 2, highlighting the importance of communication as a core factor as stated by Nguyen and Mougenot (2022) and Singh et al (2019).

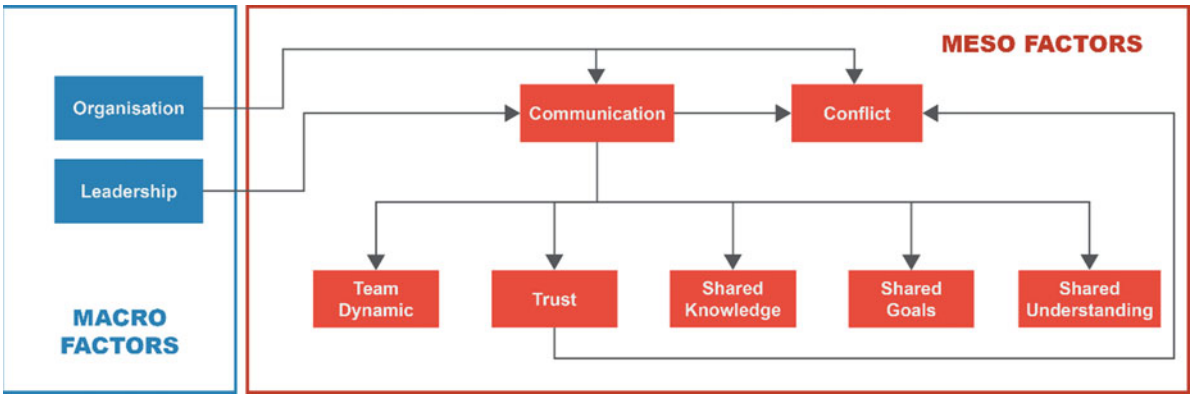

Figure 2. Communications influence on collaborative practices

Whilst most research on communication has consensus and each author builds on the contribution of one another, it is important to highlight the research that does conflict with one another, allowing consideration assessing and determining a stance on how communication impacts on the design process. Brodie (2011) explored the differences in communication skills during virtual collaboration and face-to-face collaboration. the key outcome of their study was that no matter the format of the collaboration, communication skills were always enhanced, and communication did not impact on the overall performance of the teams. Suggesting that distribution of team members does not impact on how teams work and communicate with one another. On the other hand, Nguyen and Mougenot (2022), who present a comprehensive literature review on collaboration, have suggested with global communication now readily available, cultural diversity and language differences such as cultural jargon e.g. the UK 'car boot' and the US 'car trunk', can create confusion and ineffective information sharing, aligning with Maier et al's (2021) study. However, both studies argue against Serçe et al, (2011) who studied the interaction between distributed teams and found no significance between time differences and language as an obstacle to team performance.

Maier et al (2021) expands on this and highlight some of the various factors that affect communication, they emphasis the importance of information distribution but caution that the correct information is required. Ball and Lewis (2018) align with this conclusion and expand by highlighting with the ease of access to tools to facilitate global communication, teams now can spread knowledge effectively without cost or complex organisational procedures (Macro Factor). As the network of people become dispersed and greater emphasis on information flow needs to be applied. This suggests that whilst having a distributed design presence in team working, it is harder for information to be spread and effectively understood. By relating this to other literature within engineering design, it can be suggested that a breakdown in communication is related to shared understanding (Cash et al, 2020; Nguyen & Mougenot, 2022). Wynn and Maier (2022) explore feedback systems in design, and one way that individuals seek feedback is through goal-oriented actions, this suggests that when teams create goal-oriented tasks to generate feedback, they are more likely to receive the desired outcome. goal-oriented actions is by questioning and challenging, i.e. a form of communication, allows designers to gain a better shared understanding of the thoughts of the other team members within the teams. However, it has been identified that challenging others in the team may not always led to the desired goal-oriented feedback and could result in conflict between team members (Nguyen & Mougenot, 2022; Schenteler et al., 2015; Yap et al., 2020). Nguyen and Mougenot (2022) alongside Schenteler et al (2015) and Yap et al (2020), have highlighted that conflict can create a breakdown in communication with then leads to other aspects such as trust being affected. It is important to now understand how trust impacts on the collaborative process. Yamada et al (2015) highlights that there is a lack of clarity in what individual team members perceive as common knowledge, leading to misunderstandings and the collaborative process. As highlighted by Nguyen and Mougenot (2023) misunderstandings from communication and perceptions can lead to conflict, distrust, and reduce overall performance.

Therefore, as argued in section 3.2 we do not definitively know how communication influences the development of SMMs, but the literature above can provide us a basis for understanding how communication and conflict can influence the development of a SMM.

4.3.2. Trust and team dynamic

Trust relates to the confidence actors have with one another to undertake and complete an activity involved within a collaborative project. Team dynamic on the other hand, relates to the relationship developed between actors in a collaborative project, Team Dynamic includes aspects such as team cohesion and a wider social relationship within a team. Figure 3 displays the relationships found in literature between trust and team dynamic. Trust is identified as one of the key factors that affect collaboration (Nguyen & Mougenot, 2022) as it defines the working relationship between individuals. If trust breaks down, individuals may begin to not contribute or produce unfavourable results, which supports the point made by Badke-Schaub et al., (2007) where teams need to gain trust in order to develop a SMM.

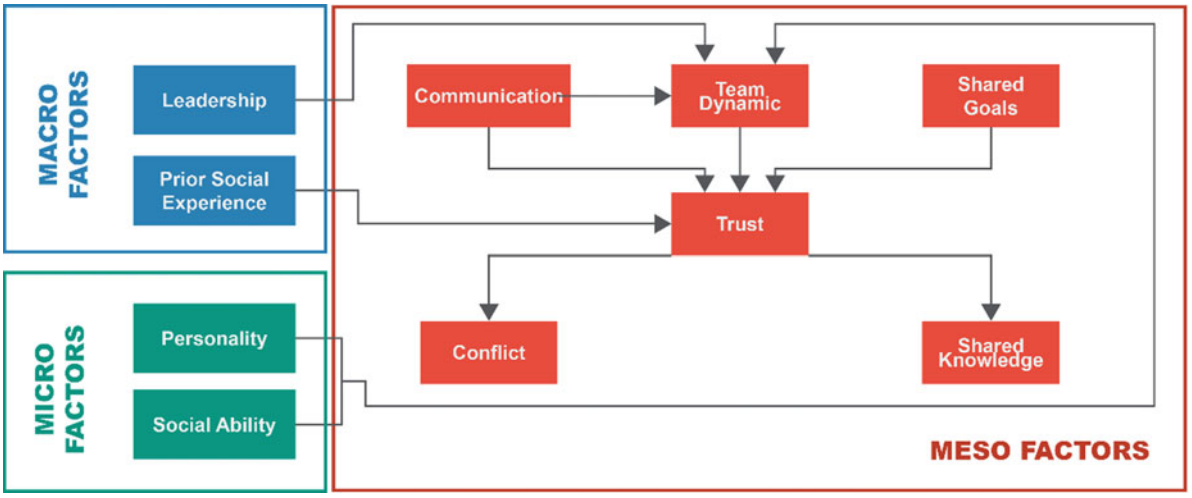

Figure 3. Trust and its influence on shared mental model development

Micro factors such as personality and social ability have been found to impact the team dynamic, more specifically the relationships formed within a team dynamic. Singh et al (2022) highlights those aspects such as team dynamics various across teams due to the mode of collaboration (i.e. face-to-face or distributed), though they do not elaborate on this point further – signifying that when assessing the team dynamic of teams there is a need to consider the role of electronic based and face to face medians impact on an individual's personality and social ability. In terms of macro factors, prior social experience has been found to provide a foundation for natural trust to be built. The two meso factors; Team Dynamic and Trust impact upon each other. Casakin and Badke-Schuab (2017) highlight that a team dynamic acts as a parallel activity to the design activity as a positive and cohesive dynamic is required to ensure any issues that arise during collaboration do not escalate into conflict, aligning with points raised by Borrego et al (2013), Nguyen and Mougenot (2022), Schnetler et al (2015) and Yap et al (2020). Therefore, to build trust, teams need to have a positive dynamic and when trust has broken down then teams are likely to develop a negative dynamic. As highlighted in section 4.3.1, communication impacts on both team dynamic and trust. Yap et al (2020) explains that when there is a lack of trust in a team, individuals will be unlikely to share certain pieces of information with one another. Leading to a conclusion that trust affects shared knowledge as communicating information is a form of shared knowledge (Nguyen & Mougenot, 2022). A breakdown in communication and trust can also lead people to work independently, Borrego et al (2013) calls this pooled interdependence, where individuals will work independently and then bring the outcomes together at the end, at this stage it is unclear the impact pooled interdependence has on team performance.

Yap et al (2020) also explains that whilst effective communication is essential to forming trust within teams, shared goals are needed for teams to build trust. Shared goals affect the development of trust, and the levels of trust impact upon shared knowledge. It has been highlighted that communication impacts on

shared understanding. Therefore, it is important to understand how shared understanding and other forms of sharedness influence SMM development.

4.3.3. The shared triad

The shared triad includes three factors; shared understanding, a communicative act where meaning is derived and passed onto other parties (Cash & Maier, 2016) which is essential to team performance (Cash et al., 2020); shared knowledge, information and learning activities that are disseminated through communicative behaviours that will improve team working (Kolbe and Boos., 2019; Kunrath et al., 2020); and shared goals, common goals derived by the team that lead to successful team working (Badke-Schaub & Hofinger, 2018). These factors are intertwined as one does not exist without the other, as shared understanding will directly influence shared knowledge and influence shared goals which in turn effects on the shared understanding as displayed in Figure 4.

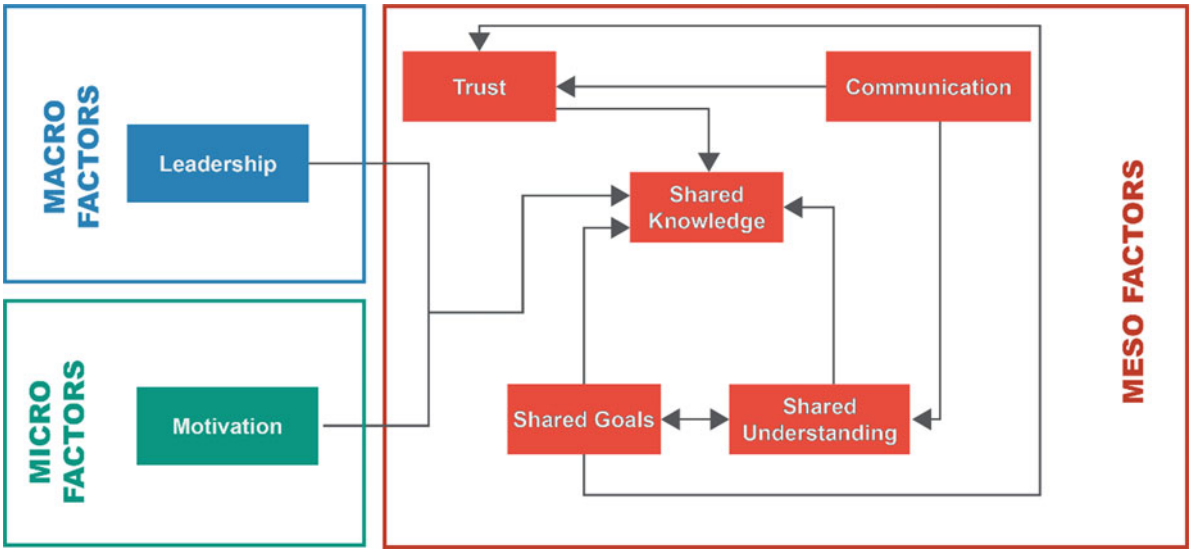

Figure 4. Shared triads influence

4.3.4. Shared understanding

Cash et al (2020) has highlighted that shared understanding has received significant research attention in team processes but shows a gap in research in terms of understanding the concepts impact on performance. As highlighted previously by Nguyen and Mougenot (2022) the level of trust between individuals impacts on the development of shared understanding and the level of communication between individuals' impact. Cash and Maier (2016) also explore the way in which communication impacts on the development of shared understanding, primarily explore other forms of communication rather than verbalisations, such as gestures. Their study highlights that the use of gestures when trying to communicate physical ideas (prototypes or artefacts) improved the development of shared understanding within teams and overall would lead to a better performance. It is argued that designers need to obtain a shared understanding before they can develop a SMM, however, it is unclear how this influences the development of SMMs.

4.3.5. Shared knowledge

Shared knowledge research has been described as non-existent in collaboration research (Schepers et al, 2019), therefore it is required to look at the knowledge of an individual and the behaviours associated. Kolbe and Boos (2019) has acknowledged that knowledge must be gained to ensure effective teamwork.
Kunrath et al (2020) has explained the development of an individual's knowledge will lead to the development of relationships, suggesting that shared knowledge will impact upon trust, team dynamics, and influence an individual's social ability. Ngyuen expands on this further an explains that shared knowledge actions can create mutual agreements, leading to a decrease in conflict within teams and an improvement in shared understanding. Yap et al (2020) reveals that to promote knowledge sharing activities, teams need to develop a SMM of the problem and how to solve said problem.

4.3.6. Shared goals

Maier et al (2021) emphasize that shared goals can contribute to conflict within teams, as when individuals disagree on how to achieve the goal, communication can breakdown and lead to conflict. Aligning with Yap et al (2020) who states that team members are more trustworthy when individuals share a common goal which in turn improves the shared understanding of the team dynamic. Schaub (2014) states that teams need a common goal to develop a SMM but once again, it is unclear how this influences a SMM.

5. Understanding shared mental model development

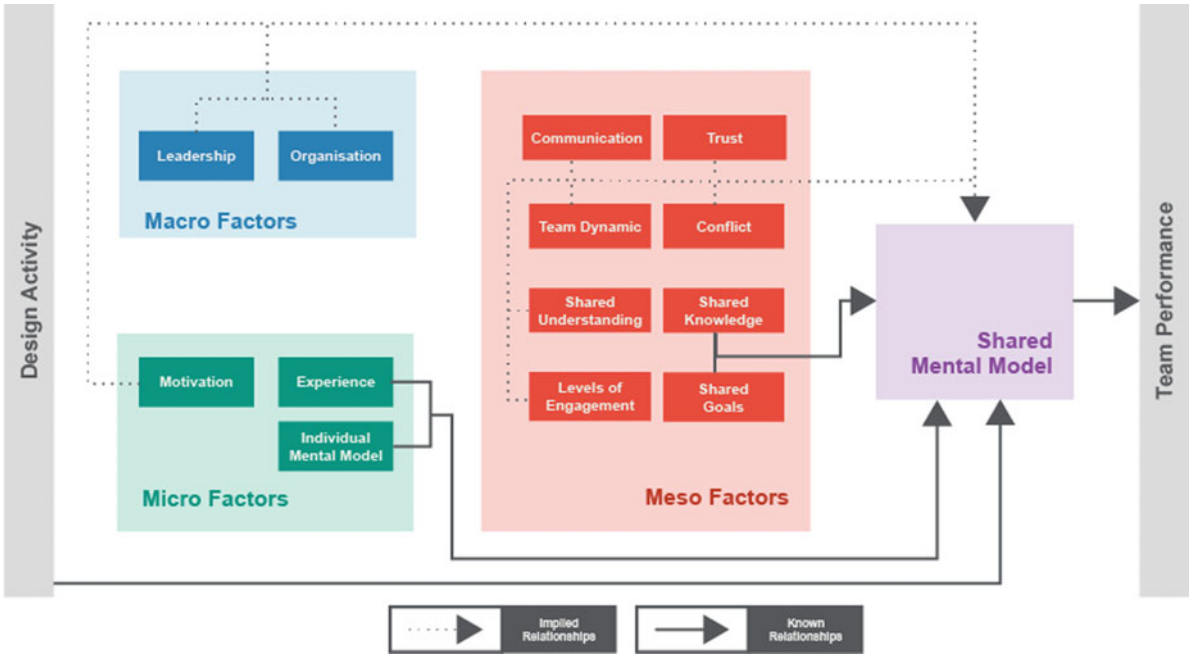

Figure 5. New framework for understanding shared mental model development

From the questions posed throughout this review, a framework has been developed mapping the various factors (Micro, Meso and Macro) in an attempt to gain a better understanding of how SMMs develop. Established in Section 3, there is still a lack of understanding on how SMMs develop within engineering design. This literature review aims to address this knowledge gap by mapping known factors (Micro, Meso and Macro). Figure 5 maps these factors into a new framework for understanding the development of SMMs within engineering design, the figure highlights the factors that impact on SMM development in contrast to the Figures 2-4 where the interlinks between the factors is explored. The relationships proposed are not definitively proven but provides us a stable ground to begin investigating further. Our known relationships: shared knowledge, shared goals, communication, experience, and Individual Mental models is built from the research conducted by Badke-Schaub et al. (2007), and Casakin and Badke-Schaub (2017). We propose that these factors have an impact on the development of a SMM, but the extent to which or how is unknown. This framework should be used to further investigate how SMMs develop during the design process. By identifying how they develop, we can begin to understand the impact they have on the success of the design process.

6. Conclusions

This systematic literature review provides a exploration of Shared Mental Models (SMMs) in engineering design, highlighting a gap in understanding how these models develop within design teams. Existing research has predominantly focused on measuring and mapping SMMs, yet little is known about the specific factors that influence their formation. This study identifies key factors–such as communication, conflict, shared goals, and trust-that are likely to contribute to SMM development.

To address this gap, we propose a novel framework that maps these factors into micro, meso, and macro-level influences on SMM formation. This framework serves as a foundation for future empirical studies, which should explore the extent to which these factors shape the development of SMMs. Understanding these dynamics will not only advance theoretical knowledge but also provide practical insights for improving collaboration, decision-making, and overall team performance in engineering design.
Future research should focus on testing the proposed framework in real-world settings, employing qualitative and quantitative methods to validate the relationships identified. Additionally, uncovering potential hidden factors that influence SMMs could further refine our understanding of team cognition. By bridging these gaps, the field can move towards a more comprehensive model of SMM development, ultimately enhancing the effectiveness and efficiency of design collaboration.

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