Working Memory, Cognitive Load, and Role of Emotions

Preeti Vijayakumar
Human Factors in Information Design, Bentley University
HF 700: Foundations in Human Factors
Dr. William Gribbons
May 6, 2024

Working Memory, Cognitive Load, and Role of Emotions

The term 'working memory' (WM) denotes the temporary storage of information while performing cognitive tasks like reading, problem-solving, or learning (Baddeley, 1983). It consists of a limited-capacity central processor, facilitating thought manipulation and essential for organizing goal-directed behavior and decision-making (Miller, Lundqvist & Bastos, 2018). Proficiency in complex cognitive processes such as language comprehension, reasoning, planning, hypothetical thinking, and creative problem-solving correlates with working memory capacity (Klaus, 2009). Long-term memory (LTM) contributes to WM by activating existing representations and incorporating new structural information for later retrieval (Klaus, 2009). In contrast to unlimited abilities like LTM storage, our conscious expression is limited to a few thoughts at a time, potentially shaping the cognitive architecture of our brains, leading to the evolution of the ability to focus on one task at a time (Miller & Buschman, 2015). When task demands exceed WM capacity, increased cognitive load degrades task performance. WM engages various cortical regions, including executive functions associated with the frontal cortex, such as planning, decision-making, attention control, and memory manipulation, alongside posterior cortical areas that maintain specific content in visual, spatial, and auditory formats (Miller & Cohen, 2001). These cognitive abilities helped early humans outsmart predators and compete for resources. Understanding working memory's limitations and its impact on task performance allows UX designers to optimize interface design, minimize cognitive load, and foster positive user experiences.

This paper examines WM components, its key characteristics, cognitive load, and the impact of anxiety and motivation on WM performance, followed by a design review of the Calendly appointment booking service.

Components of Working Memory

Baddeley and Hitch's *multi-component model* of the WM originated in 1974. By 2000, the model proposed a system with four key components: the central executive, the phonological loop, the visuospatial sketchpad, and the episodic buffer. The *central executive* serves as the "conductor" of working memory, directing attention, coordinating cognitive tasks, and switching between different mental activities. It plays a crucial role in higher-order cognitive processes such as problem-solving, decision-making, and goal-setting. The *phonological loop* is responsible for processing auditory and verbal information; the phonological loop consists of two subcomponents: the *phonological store*, which holds auditory information briefly, and the *articulatory rehearsal process*, which maintains and refreshes verbal content through silent speech. This loop is essential for tasks involving language comprehension, repetition, and verbal working memory. Similarly, the *visuospatial sketchpad* is a mental workspace for visual and spatial information and enables us to mentally manipulate images, visualize spatial relationships, and navigate through imagined environments. It plays a crucial role in tasks such as mental imagery, spatial navigation, and visual problem-solving. Finally, the *episodic buffer*, added later to the model, serves as a temporary storage system that integrates information from various sources, including the other components of WM and LTM. It binds together different features into coherent episodes, forming complex mental representations and facilitating the integration of new information with prior knowledge. (Baddeley, Allen & Hitch, 1983)

Characteristics of Working Memory

Limited Capacity

Capacity, an important aspect of WM, refers to a limited amount of resources available for allocation to processing and storage functions (e.g., Baddeley & Hitch, 1974). The multi-component model is aligned with the *fixed capacity theory*. It proposes that performance differences among individuals within a task domain can be explained in terms of WM capacity. When task demands are high enough to strain capacity, individuals with a lesser capacity are predicted to be less able to process information in a timely fashion or to store intermediate products (Baddeley, 1983; Sohn & Doane, 2003). Miller (1956) explored the fixed capacity theory. He suggested that the average person can hold about seven (plus or minus two) "chunks" of information in their working memory at any given time (Miller, 1956). Miller's term "chunk" refers to a meaningful unit of information that can be grouped. These chunks could be digits, letters, words, or other meaningful units that the individual perceives as a single entity. Spatial binding leads to the perception of chunks as separate entities, concurrent with the law of proximity. Cognitive binding, with prior knowledge from the LTM, allows the perception of chunks as unified wholes.

As an alternative to the fixed capacity theory, in the *skill-based theory* (Ericsson & Kintsch,1995) or *dynamic capacity theory*, working memory (WM) capacity is linked to an individual's expertise in accessing task-relevant information efficiently from long-term memory (LTM). This theory, known as *long-term working memory (LTWM)*, posits that WM capacity can dynamically change based on one's proficiency in accessing information stored in LTM. Experts develop retrieval structures through extensive domain-specific knowledge, enabling them to surpass WM capacity limits (Sohn & Doane, 2003). In 2001, Cowan proposed a notion that also aligned with a dynamic capacity. He suggested that working memory capacity is limited not by the number of items it can hold, but rather by the amount of attentional resources available to allocate to those items. Opposite to Miller's views, Cowan said that the WM can hold a relatively small number of items (around four chunks of information) in a highly accessible state, but it can maintain a larger number of items in a more passive state that requires less attentional resources (Cowan, 2001). He went on to suggest that individuals could improve their memory capacity by engaging in activities that enhance attentional control, such as memorization, using memory techniques like chunking and mnemonics, minimizing distractions, and practicing dual-tasking activities to manage competing demands on working memory. (Cowan, 2010)

Furthermore, fluctuations in the operational capacity of working memory (WM) can be attributed to factors like age, impairments, or levels of expertise (Cowan, 2010). These limitations in capacity may arise from biological constraints associated with the energy cost of maintaining a larger capacity or enhancing search efficiency to reduce confusion and distraction (Cowan, 2010).

Limited Duration

Another notable feature of working memory is its inherent limitation in duration. Peterson and Peterson (1959) highlighted the temporal dimension, observing that memory traces undergo decay over time. This temporal constraint creates a trade-off between processing and storage, where resources allocated to one function become unavailable for the other (Barrouillet et al., 2004). Even without new information being introduced, memories within working memory fade over time. This decay is a natural process to prevent overloading the system and allow for the processing of new information. The impact of time constraints presents challenges for working memory in supporting various cognitive tasks that demand extensive resources, such as decision-making processes influenced by bounded rationality theory (Paas et al., 2003). For instance, when individuals make decisions under time pressure, they may rely on heuristics and biases to prioritize speed and efficiency rather than engaging in comprehensive information processing. (Gigerenzer & Gaissmaier, 2015)

Volatility

The volatility of working memory refers to its dynamic nature, characterized by the constant updating and modification of information stored temporarily for cognitive processing. This volatility is evident in the complex processes of perception and memory, which involve both feedforward and feedback systems (Tulving, 1972). External distractions or internal attention shifts can disrupt the focus on information held in working memory, leading to its deterioration or displacement (Loschky, 1998). The impact of interruptions, especially for older adults, can further exacerbate selective interference effects in working memory components like the phonological loop and visuospatial sketchpad (Baddeley & Hitch, 1998).

Cognitive Load

Cognitive Load Theory (CLT) originated in the 1980s and saw significant development in the 1990s, becoming a major framework for investigations into cognitive processes and instructional design. It posits that individuals have limited cognitive resources available for processing information, and when these resources are exceeded, learning is impaired. In short, cognitive load refers to the mental effort required to process information during learning (Sweller & Chandler, 1994). Sweller (2011) defines three kinds of loads: intrinsic, extraneous and germane. *Intrinsic load* is the inherent difficulty associated with the learning task itself. It is determined by the complexity of the material being learned and the learner's existing knowledge and expertise in the subject. It cannot be altered by instructional design but can be managed by breaking complex tasks into smaller, more manageable components (Sweller, 2011). *Extraneous load* refers to the additional mental effort imposed by the instructional design or learning environment that is not directly related to the learning task. Extraneous cognitive load arises from factors such as poorly designed instructional materials, confusing presentation formats, or irrelevant distractions (Sweller, 2011). *Germane load* relates to the mental effort expended on meaningful learning processes, such as organizing, integrating, and elaborating new information into existing cognitive schemas. It is beneficial for learning as it contributes to the construction of deeper understanding and long-term retention of knowledge. It is influenced by instructional strategies that promote active processing, meaningful engagement, and deep learning.

Cognitive load effects (Sweller, 2011) encompass various phenomena that illustrate how the cognitive demands imposed by learning tasks can impact learners' performance and understanding. The *goal-free effect* suggests that when learners are presented with a problem without explicit goals or instructions, they may explore more diverse problem-solving strategies, fostering creativity and deeper understanding. Conversely, the *worked example effect* demonstrates that providing learners with step-by-step examples of problem-solving procedures can facilitate learning by reducing cognitive load and promoting schema acquisition. *Split attention effects* occur when learners are required to split their attention between multiple sources of information, leading to cognitive overload and decreased comprehension. *Modality effects* suggest that presenting information in multiple modalities (e.g., text and visuals) can enhance learning by reducing cognitive load and facilitating dual processing (Low et al., 2011). However, the *redundancy effect* warns against including redundant information across modalities, as it can increase cognitive load without enhancing learning (Sweller, 2011). UX designers can minimize extraneous load and optimize performance by understanding these effects and including metacognitive techniques.

Emotions - Role of Anxiety and Motivation in Working Memory

Emotion plays a significant role in influencing WM performance, with both anxiety and motivation exerting distinct effects on cognitive functioning. *Anxiety* is characterized by feelings of apprehension or worry that occur in the WM. High levels of anxiety can impair WM performance by diverting all cognitive resources towards monitoring and processing threat-related information (Eysenck et al., 2007). This allocation of attention towards anxiety-inducing stimuli can lead to decreased capacity for processing task-relevant information, resulting in impaired performance (Baddeley, 2012). Additionally, anxiety can disrupt executive functions such as attentional control and inhibition, further exacerbating cognitive deficits (Moran, 2016).

Conversely, *motivation*, defined as the drive to achieve goals or rewards, can enhance WM performance by increasing attentional focus and cognitive engagement. Low levels of anxiety could act as motivators, inhibiting interrupting thoughts and making us focus all of our resources on a task. Motivational factors activate reward-related neural circuits (goal of gamification), facilitating the allocation of cognitive resources toward task-relevant information processing (Randhawa et al, 2022). This heightened cognitive engagement leads to improved encoding, retention, and retrieval of information in working memory. Furthermore, motivation can enhance strategic processing and cognitive flexibility, enabling individuals to adaptively allocate resources to meet task demands. Understanding the interplay between emotion and working memory can inform design decisions aimed at optimizing cognitive performance.

Design Review: Calendly

Calendly is a cloud-based appointment-scheduling software that simplifies the process of scheduling and meetings.

1. It has a smooth onboarding process with steps on the side on the Home screen (Fig 1a) to learn for novices. The steps section remains open as long as the user requires it to be. This reduces the cognitive load on novices to remember the steps. Video tutorials (Fig 1b and 1c) can be replayed any number of times to understand and rehearse the required steps before they need to apply them. Experts, who may have used Calendy or other scheduling apps earlier can close this tab.

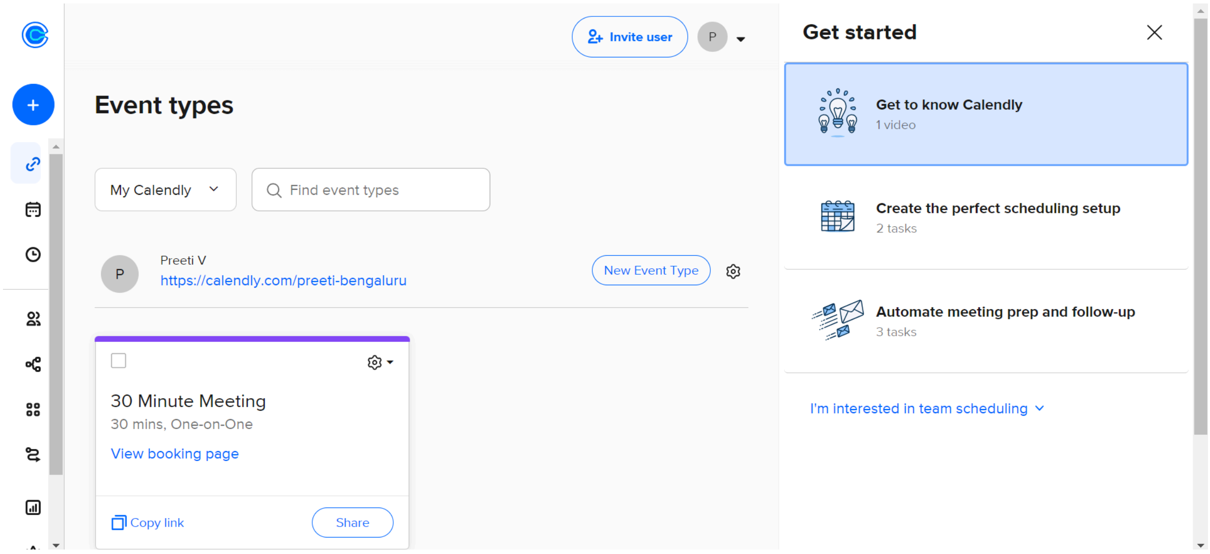

Fig 1a: Onboarding Home - Option to learn steps (for novices) or ignore them (for experts)

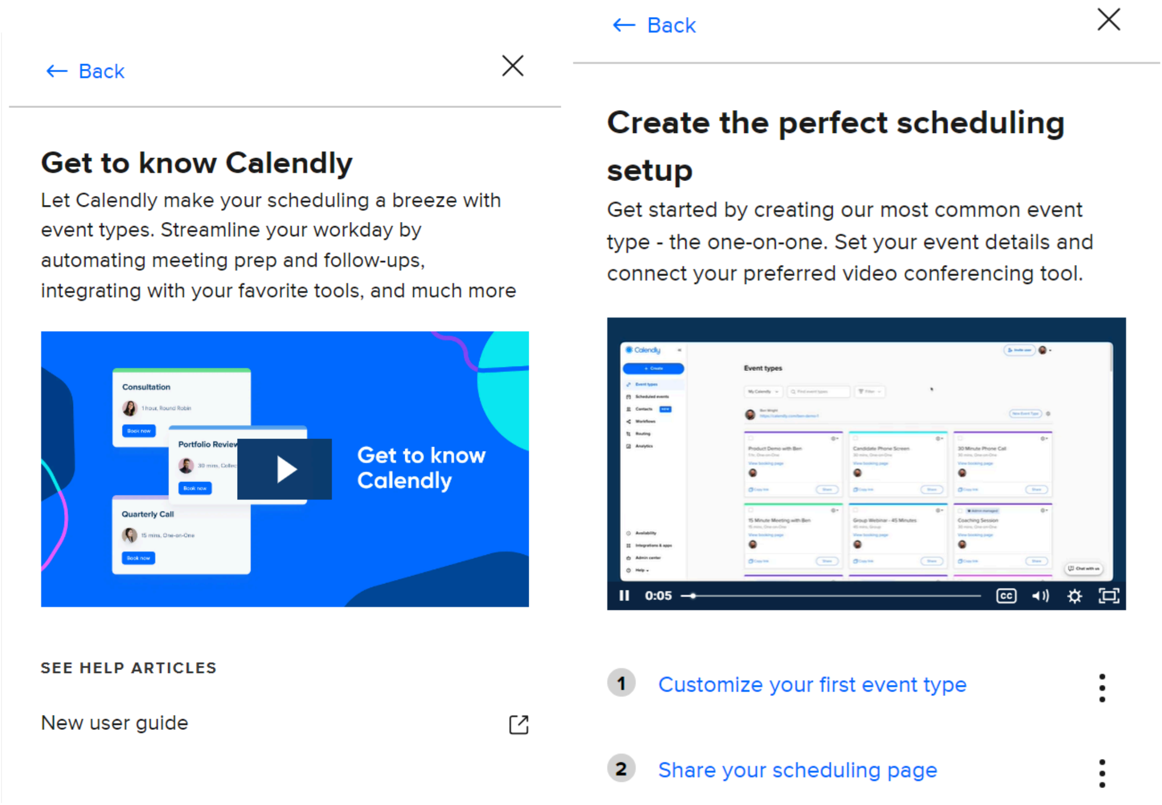

Fig 1b and 1c: Stepwise video tutorials

2. They have a very clear "create" button to get started with setting up a schedule for the appointment. This procedure has a number of steps including event details, hosts and invitees, and scheduling settings amongst others. Each of these steps has a reminder popup, along with an explanation. Despite watching the tutorial, if novices have doubts, this should guide them along the way.

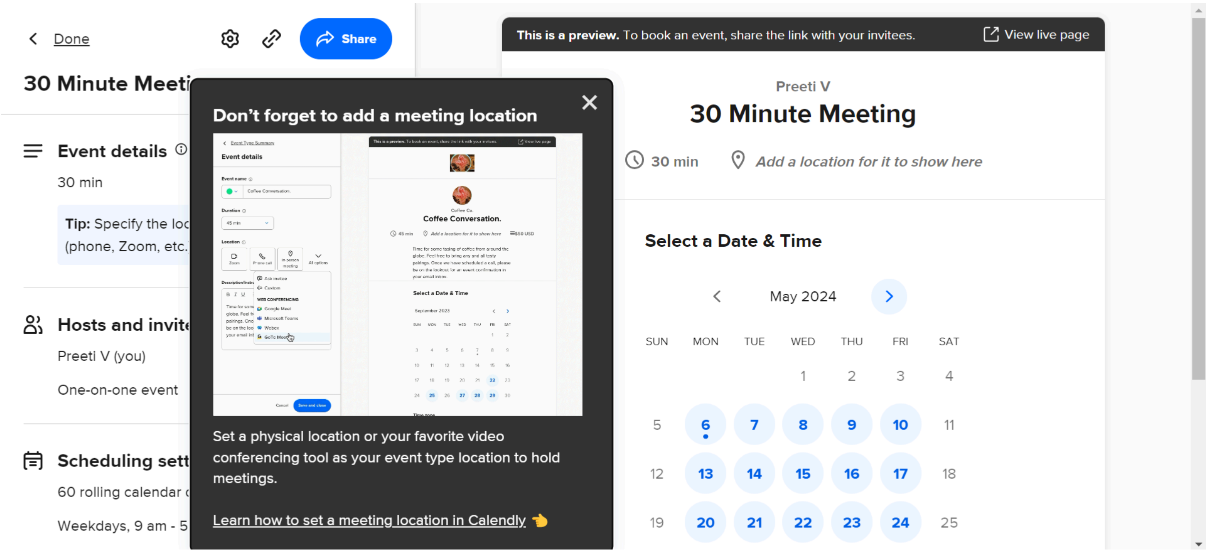

Fig 2: Guidance for each step in setting up a schedule

3. Users can set up fixed or custom durations for calls based on their schedule. Users with limited working memory may prefer shorter call durations to avoid cognitive overload during meetings, while others may benefit from longer durations to accommodate complex discussions or collaborative work sessions. By giving users control over the duration of their calls, Calendly helps to optimize their cognitive load and enhance their overall productivity and well-being.

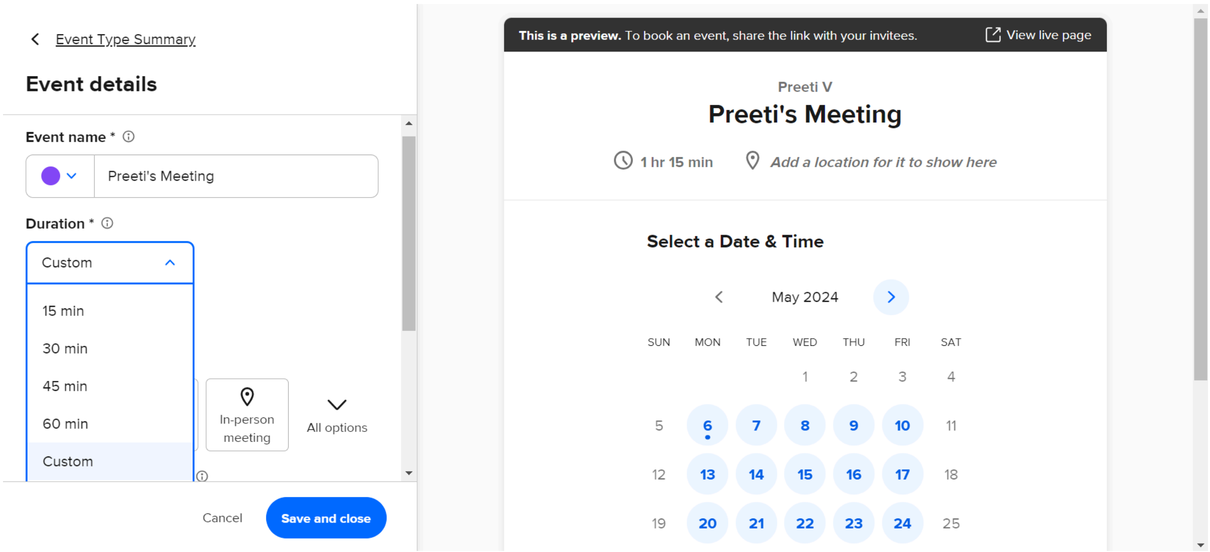

Fig 3a: Custom call durations

However, booking timeslots on the booker's end are always multiples of 30 minutes. This sometimes reduces the effect of offering custom call durations unless they are multiples of 30 minutes.

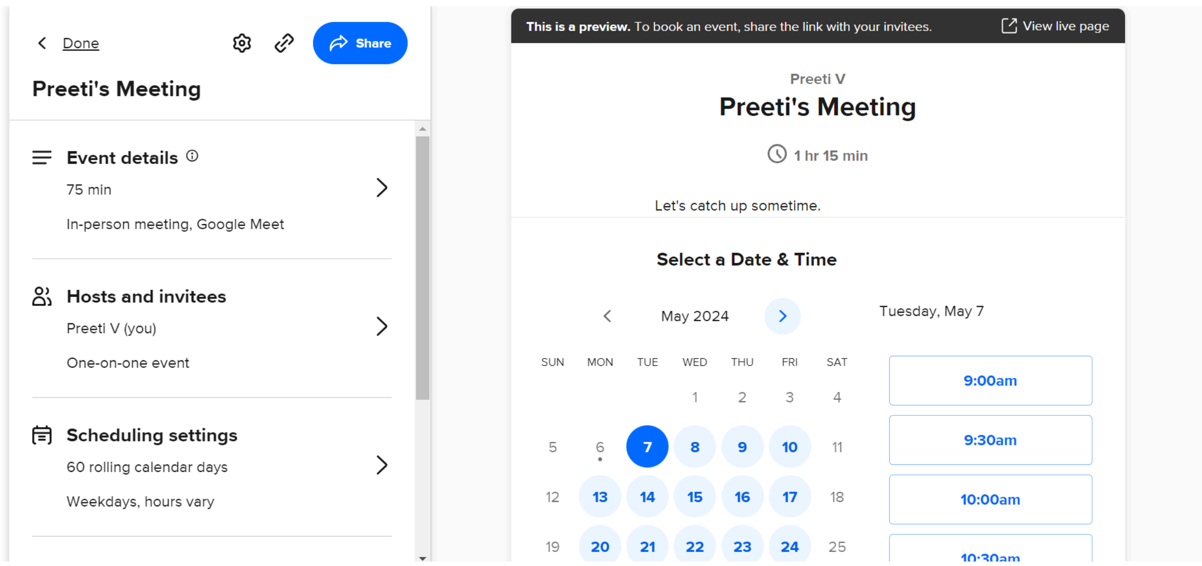

Fig 3b: On the right, user can view how their calendar will look to a booker

4. The user can also set up upto 6 different calendar apps with Calendly (such as those of Google, Microsoft, etc). The software ensures that a scheduled time is booked on all of them so that there is no overlap. This allows users to plan and organize their schedules effectively, reducing the cognitive load associated with remembering and managing multiple appointments.

5. Calendly increases efficiency with pre-existing streamlined workflows to remind bookers about upcoming appointments and condenses repetitive tasks into automatic communications such as sharing an invite via email and text. This reduces burden to carry out these tasks on the user and increases their efficiency.

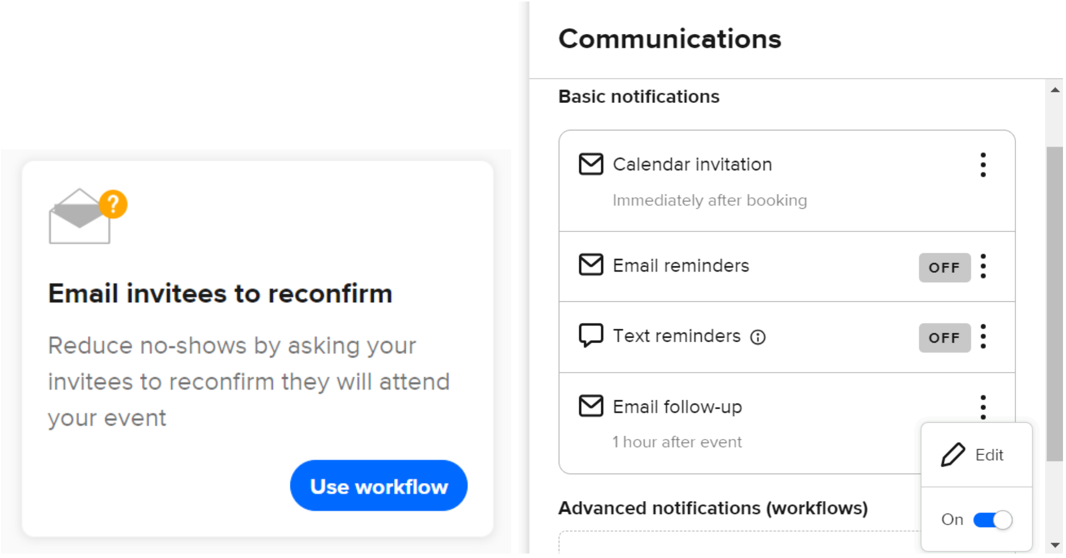

Fig 5: Automatic workflows

By applying the principles of cognitive load theory to UX design, designers can create interfaces that are more user-friendly, efficient, and enjoyable to use, ultimately enhancing the overall user experience.

Conclusion

References

Baddeley, A. (2020). Working memory. In *Memory* (pp. 71-111). Routledge.

Baddeley, A. D., Allen, R. J., & Hitch, G. J. (2017). Binding in visual working memory: The role of the episodic buffer. *Exploring Working Memory*, 312-331.

Baddeley, A, Papagno, C., & Vallar, G. (1988). When long-term learning depends on short-term storage. *Journal of Memory and Language*, 27, 586-595.

Barrouillet, P., Bernardin, S., & Camos, V. (2004). Time constraints and resource sharing in adults' working memory spans. *Journal of experimental psychology: General*, *133*(1), 83.

Cowan, N. (2008). What are the differences between long-term, short-term, and working memory?. *Progress in brain research*, *169*, 323-338.

Cowan, N., Elliott, E. M., Saults, J. S., Morey, C. C., Mattox, S., Hismjatullina, A., & Conway, A. R. (2005). On the capacity of attention: Its estimation and its role in working memory and cognitive aptitudes. *Cognitive psychology*, *51*(1), 42-100.

Ericsson, K. A., & Kintsch, W. (1995). Long-term working memory. *Psychological review*, *102*(2), 211.

Eysenck, M. W., Derakshan, N., Santos, R., & Calvo, M. G. (2007). Anxiety and cognitive performance: attentional control theory. Emotion, 7(2), 336.

Gigerenzer, G., & Gaissmaier, W. (2015). Decision making: Nonrational theories. In International encyclopedia of the social & behavioral sciences (pp. 911-916). Elsevier

Grogan, J. P., Randhawa, G., Kim, M., & Manohar, S. G. (2022). Motivation improves working memory by two processes: Prioritisation and retrieval thresholds. *Cognitive Psychology*, *135*, 101472.

Hur, J., Iordan, A. D., Dolcos, F., & Berenbaum, H. (2017). Emotional influences on perception and working memory. *Cognition and Emotion*, *31*(6), 1294-1302.

Loschky, L. (1998). What Is Working Memory?.

Low, C., Chen, Y., & Wu, M. (2011). Understanding the determinants of cloud computing adoption. Industrial management & data systems, 111(7), 1006-1023.

Miller, E. K., & Buschman, T. J. (2015). Working memory capacity: Limits on the bandwidth of cognition. *Daedalus*, *144*(1), 112-122.

Miller, E.K., and Cohen, J.D. (2001). An integrative theory of prefrontal cortex function. *Annu. Rev. Neurosci*. 24, 167–202.

Miller, E. K., Lundqvist, M., & Bastos, A. M. (2018). Working Memory 2.0. *Neuron*, *100*(2), 463-475.

Miller, G. A (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review*, 63, 81-97.

Moran, T. P. (2016). Anxiety and working memory capacity: A meta-analysis and narrative review. *Psychological bulletin*, *142*(8), 831.

Paas, F., Renkl, A., & Sweller, J. (2003). Cognitive load theory and instructional design: Recent developments. *Educational psychologist*, *38*(1), 1-4.

Peterson, L., & Peterson, M. J. (1959). Short-term retention of individual verbal items. Journal of experimental psychology, 58(3), 193

Sohn, Y. W., & Doane, S. M. (2003). Roles of working memory capacity and long-term working memory skill in complex task performance. *Memory & Cognition*, *31*(3), 458–466. https://doi.org/10.3758/bf03194403

Sweller, J. (2010). Element interactivity and intrinsic, extraneous, and germane cognitive load. *Educational psychology review*, *22*, 123-138.

Sweller, J. (2011). Cognitive load theory. In *Psychology of learning and motivation* (Vol. 55, pp. 37-76). Academic Press.