Intermittent Interaction in Digital Fabrication

User Perception of Periodic Intervention in Semi-Automated Creation Tasks

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Abstract

Intermittent Interaction is a turn-taking approach used to interact with fabrication devices to do something that otherwise would be impractical or impossible for the machine. We investigate how people perceive intermittent interactions in a controlled study. A LEGO assembly task with timed lock boxes simulates human involvement with a semi-automated machine process, similar to a 3D printer. This is used in an in situ study with 12 participants over 4-hour sessions with experimental controls for number of interactions and step complexity. Results suggest complex interactions during assembly can amplify the perceived value of the assembled object and increase enjoyment. Participants used either a clustered or evenly distributed strategy to schedule interactions, which can be modelled with simple heuristics. We contribute evidence that intermittent interaction is generally acceptable for creation tasks and practical guidelines for integrating intermittent interactions into semi-automated fabrication systems.

CCS Concepts

• **Human-centered computing → User studies**.

Keywords

intermittent interaction, controlled experiments, personal fabrication

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1 Introduction

Many digital fabrication processes occasionally require someone to briefly intervene to do something that would be impossible or impractical for a fabrication machine. Consider using a fused deposition modelling (FDM) 3D printer. In between starting a print and removing the result from the build plate several hours later, the user may also need to replace empty filament spools, switch between filament colours, and even handle faults like clogged nozzles or collisions. Researchers have proposed print-pause-print fabrication techniques that require similarly brief user interactions with personal fabrication machines. In many of these techniques, fabrication is paused once to insert small objects to increase the capabilities or interactivity of the fabricated items, such as adding sensors [10, 53], actuators [12, 15, 38], specialized mechanisms [13, 19, 20, 33], and further types of inserts [7, 8, 39, 48]. Recent work has expanded this approach to multiple brief user interactions to make printing processes faster and more sustainable by replacing printed sections [36, 49], enable novel output options by assembling mechanical primitives as part of the fabrication process [22], and support creative expression by manually adjusting the output shape in between fabrication steps [41, 51]. In all of these examples, the user and machine take turns to jointly create an item, but the user's interactions are sparse and short relative to machine processes.

We refer to this kind of turn-taking approach as *Intermittent Interaction.* In the context of personal fabrication, intermittent interaction describes periodic user interactions with an ongoing fabrication process with prolonged breaks between interactions, typically lasting tens of minutes to several hours. The objective is to combine the strengths of the user and the machine within a single long process. As in the previous system examples above, this can expand the capabilities of standard fabrication machines, especially FDM printers. Yet, the user effort to perform intermittent interactions is rarely considered. As systems start to employ more frequent and more complex interactions, it becomes even more important to consider these costs.

We report on a controlled study to investigate how people perceive varying levels of intermittent interactions, including preferences for when interactions occur, and what effect they have on the subjective value of the object being made.

Our focus is on creation tasks, rather than routine maintenance, through the creation of physical artifacts. The protocol asks participants to assemble LEGO models at controlled time intervals over several hours. Like intermittent interactions with fabrication systems, a LEGO assembly task requires dexterity and precision with physical manipulation, and the user must adhere to a predefined series of steps over time. LEGO also makes it feasible to conduct a long-duration take-home study, and to strictly control for interaction *complexity* and *density* [49] by varying the number of LEGO bricks placed per assembly step and varying the frequency and distribution of assembly steps. Not only has LEGO been used before to represent other materials in creation tasks [37], but assembling

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LEGO objects has been used directly in intermittent interaction systems [49]. Moreover, the primary goal of using personal fabrication devices is typically the creation of an item, and the specifics of how the item is made is often a means to that end.

In all communication with participants, we framed the study as a representation of turn-taking with a fabrication machine. We discuss limitations of our approach in section 6.

We recruited 12 participants to each assemble three different LEGO models, with the assembly steps of each model distributed over a 4-hour time frame. This was accomplished using multiple custom "lock-boxes", each containing LEGO pieces and a link to online assembly instructions. SMS notifications were sent to the participant at controlled times with a combination code to unlock the next box in sequence. The number of bricks per assembly step created three levels of *complexity* (1, 4, or 12 bricks) and the number of assembly steps created three level of *density* (2, 4, or 8 notifications). Our system logged how long it took to respond to each step notification and when the step was completed. After all steps for a model were completed, we asked about mental demand, annoyance, enjoyment, and feeling of contribution. A post-study interview asked how each participant valued their completed LEGO models, what their general experience was for this style of intermittent manual tasks over a long period, and what kind of task schedule they preferred.

Overall, our results identify themes for intermittent interaction: the effort of interacting intermittently was typically acceptable across the full investigated interaction density range, with up to eight interactions during a four hour process; the progression of making an object over time was enjoyable; higher task complexity can increase enjoyment due to greater engagement with the process; and although performing an assembly task as an infrequent sequence of steps can feel rewarding, it can also be annoying, even stressful, depending on how the steps are distributed over time and whether the overall goal was worthwhile. Using a standard methodology [5], we demonstrate that the "IKEA effect" of self-assembly enhancing object valuation [28] extends to partial assembly over time, even when the person contributes only a portion of the assembly. We also identify two main types of scheduling strategies and propose simple prediction heuristics to identify or generate desirable schedules. Finally, we contribute guidelines to inform the design of future intermittent interactions system, and provide examples of their application to a fabrication system.

2 Background and Related Work

Our work relates to the use of AI agents, notifications, slow interactions, and the value of manual participation. We contextualize our contributions within these domains, outlining how our study augments or confirms previous findings. Finally, we examine semi-automated fabrication where our contributions can be used to justify, improve, and extend this family of approaches.

Note than in the context of AI, the term intermittent interaction describes a fully user driven turn taking approach [47]. This differs from our definition in the context of making physical items, where prolonged processes are common and where the interaction can be initiated by the system after a waiting period, for example in the form of requesting manual assistance from the user.

2.1 Notifications Prompting Interaction

Our study makes extensive use of phone notifications. Prior work shows that the majority of notifications are either handled immediately (e.g. within 30 seconds) or after a long time (e.g. more than 8 minutes) [35]. Our study confirms these findings. Previous work further finds that notifications are only considered bothersome if they are deemed superfluous, such as ads, uninteresting content suggestions, or reminders for expected events [35]. Although the notifications in our study were expected, they were typically still deemed important and addressed promptly. About half of the notifications in our study were addressed right away. For comparison, three quarters of email notifications are typically ignored [18], even though they can be handled on the same device that sent the notification, while study tasks may require relocating.

2.2 Slow Interactions at Home

Photobox [30] is an interactive piece of furniture that occasionally prints photos and is designed to reflect on the role of technology at home. The work demonstrates people will change their routine to include technology, just like regularly checking up on an ongoing 3D print, but only if the encounters are deemed meaningful. We also observed participants structuring their day around the scheduled interactions and anticipating upcoming study tasks and final outcomes.

Based on insights from The Reflexive Printer [45] where managing a large number of loose photos can be annoying, we designed our study material with storage options to avoid clutter.

The Slow Game Odom et al. [29] examines a kind of intermittent interaction in the form of slow interactions with a "snake" game where the snake only moves after many hours, to create interactions that are important but not urgent. Interacting with idle fabrication machines can similarly be delayed for many hours, and our study set no fixed deadline to complete sessions, allowing participants to delay tasks freely. The Slow Game was designed to foster "[...] rich, yet highly minimal interactions." Our study aims to determine whether minimal interactions with making processes can achieve rich connections with the made item, and whether actively prompting interactions alienates users.

2.3 Labour leads to love

The IKEA effect [28] is the idea that assembly effort increases the perceived value of an item, and that this increased valuation only persists as long as those items remain complete, that is, have not yet been disassembled again. The study found a 63% increase in valuation when participants who had assembled a piece of furniture were asked to rate and bid on it, compared to participants who only inspected the same furniture before bidding. We study a similar effect, but in a different context and scale. The finished LEGO models are always complete, but participants only performed a part of the assembly. Similar to the IKEA effect, we perform an incentive compatible value elicitation method where the dominant strategy is bidding the true value associated with the assembled model. We modify the procedure to avoid the need for participants to carry currency to participate. Existing theories on making using digital media further support the importance of physical interactions during creation tasks in finding the "intrinsic pleasures of creative action" [34], and suggest that even limited and repetitive creative actions can contribute to the intrinsic valuation and sense of ownership of an item [23].

2.4 Guiding Creation Processes

In "Being the Machine" [9], the user assumes the role of the physical actuator of a 3D printer. Instead of moving a print-head, the system only steers a laser pointer, and the user crafts an object out of arbitrary materials following this visual guide. Related to intermittent interaction, "Being the Machine" relies on human assistance, but in an extreme form without any machine automation.

Exquisite Fabrication [14] and smARt.Assembly [37] guide users to assemble artifacts using items provided from multiple fabrication machines or storage containers. The smARt.Assembly system simulates industrial assembly stations by performing assembly of LEGO bricks. We also use LEGO to simulate a creation process. The Exquisite Fabrication system allows users to coordinate and combine the outputs of multiple fabrication machines. Such a setup requires turn-taking interactions to orchestrate the different machines, demonstrating one of the types of use cases we investigate.

Systems that enable rapid prototyping are instead often fully driven by the user, who guides fabrication machines that are also capable of autonomous operation. This interactive fabrication may still involve waiting periods to allow the machines to catch up to the latest user input. Examples of such systems are On-The-Fly Print [32], RoMA [31], Interactive Construction [25], Turn-by-Wire [43], Protopiper [1], and Fabrickation [26]. The shortest wait times included in our study are 3 minutes long, which may still be relevant for such systems. For example, FormFab [27] allows shaping acrylic plates into 3D models by applying either a vacuum or positive pressure to a heated section of the plate. After designating an area that the user intends to reform, they have to wait for a few minutes while the system heats up the area, before they can take direct control of the shaping process.

2.5 Semi-Automated Fabrication

Semi-automated fabrication processes require some form of user interaction to succeed. This broad category spans from interactive fabrication, which requires the user's constant attention, to merely resetting a system at the end of batch processes to enable repeated execution. Mueller situates how the speed of fabrication allows different kinds of user interaction, from hands-off automated processes, to turn-taking, to direct manipulation [24]. Increasing the speed and interactivity of personal fabrication has been framed as one of the key challenges of the technology [3, 4].

Prior work has explored options to combine automated fabrication and user inputs in the output object by performing interactions before or after the actual fabrication. For example, Printy3D [53] allows kids to physically align electronic components into a projected outline of customized containers ahead of fabrication, and inserting the components into the container after fabrication. MiragePrinter [52] and Patching Physical Objects [42] allow modifying and printing on existing physical objects after the user mounts and secures the object within the build volume of a 3D printer. ProxyPrint [44] facilitates manual wire wrapping through 3D printed jigs, fully separating the automated and manual parts of the process, which enables semi-automated crafting without intermittent interactions. Embedded sensing [10] integrates sensors into 3D prints by performing complex manual adjustments to the object after fabrication is complete, such as melting wax support material and pumping conductive paint into the freed channels using a syringe.

We list examples of semi-automated fabrication systems with intermittent interactions in prior work ordered from low to high user interaction in the following paragraphs, starting with systems that use simple, single user interactions, and ending with systems with multiple complex interactions.

Basic Interaction. Generally, a single intermittent user interaction can materially improve the fabricated objects or speed up the fabrication process. For example, simply dropping a magnetic stirbar into a 3D printed cavity during a single printing pause allows creating a cheap, rapidly available fluidic reactor [38]. Filling a hollow chamber with a reaction mixture during a printing pause allows laboratory-scale design and production of specifically tailored reactionware [19]. Placing a porous membrane on top of a hollow chamber suffices to create a printed dialysis device [33]. Placing sensors into printed grooves has been used to fabricate miniature water quality sensing systems [2]. Scrappy [48] partially avoids printing internal support by inserting a single piece of scrap into the model. The replaced structures do not need to be fabricated, which can significantly decrease fabrication time and material usage. Encore [8] enables users to print on curved inserted objects by first printing a custom base for the object, and it supports printing through through-holes of the existing object.

Complex Interaction. Slightly more complex interactions, such as inserting a heating element strip during a printing pause while also attaching a thermistor with double-sided tape with the HotFlex system [15], have been used to produce more interactive output objects. The resulting objects can then be customized in-situ by heating the material until it becomes malleable. By heating and pressing wire made from shape memory alloy into flexible 3D prints, arbitrarily shaped actuators with shape memory can be created using readily available wire and 3D printers, rather than machining expensive alloy [12]. Medley [7] makes use of highly complex user interactions, such as carving or cutting "embeddables" like rubber or foam into shape prior to insertion into a 3D print, to adjust many mechanical properties of output objects, or even their acoustic, optical or thermal properties. Gaal et al. [13] suggest a system where a user places thin sheets of glass, paper, wires, polymers, and electrodes into printed microchannels during a single printing pause, to create an electronic tongue sensor. Hernández-Rodríguez et al. suggest enhancing 3D printed electrodes by sanding, drop-casting or electroplating them to apply coatings, or integrating devices like pumps and valves during a printing pause [16].

Multiple Interactions. By extending the user interactions to a second printing pause, prior work introduces a process that allows fabricating multi-step reactionware [20]. To create these highly versatile fluidic devices, users transfer the print to a secondary fabrication machine that applies layers of catalysts, before returning it to the FDM printer. During a second printing pause, users then fill hollow printed chambers with stirbars, reagents, or silica gel. Using additional printing pauses to insert electronic components, Shemelya et al. demonstrated fabricating a fully enclosed capacitive touch sensor including LED outputs [39]. The Flushner [36] and Substiports [49, 50] systems integrate multiple printing pauses to adjust the printing process itself, improving the speed and sustainability of 3D printing by replacing flat surfaces of objects with inserted laser-cut plates (Flushner), and by replacing printed support structures that surround the object with inserted ad-hoc assemblies, like towers of LEGO bricks (Substiports). The latter project adopted the term "density" to refer to the number or frequency of interactions.

Multiple Complex Interactions. 3D Pen + 3D Printer [41] and ReForm [51] support creative expression by making user interactions a core part of the creation process. ReForm switches back and forth between fabrication and user interactions by allowing the user to physically reform a clay version of the model, which is kept synchronized with the digital model. 3D Pen + 3D Printer allows both user and the automated 3D printer to fabricate in parallel, with the user making adjustments to printed parts, or combining sub-assemblies, while further parts of the model are being printed.

Beyond FDM 3D printing, FusePrint [54] allows fitting stereolithography (SLA) prints to existing objects by inserting a spacer of the desired size, or the object itself, into resin that is actively being cured during a single user interaction during the process. LamiFold [22] enables novel output options on a laser-cutter by assembling mechanical primitives directly as part of the fabrication process. The user inserts layers of wood or paper, applies glue to a layer, or removes off-cuts during the cutting process.

Our work takes the approach of intermittent interaction that many of these systems employ and explores it with a controlled study that covers and extends beyond the range of the typical number of user interactions. Using LEGO assembly as a controllable creation task that some of these systems use (e.g., [37, 49]), and which matches the size of inserts that most of them require handling, we directly investigate the experience of intermittent interaction and the trade-offs between complexity of interaction and their density (rate of occurrence) for a common FDM 3D printing duration.

3 Study

This study examines how the density of interactions over a long creation session, and the complexity of each interaction, can affect user experience, perceived value of an assembled item, and the effort required to complete the assembly. We also observe trends for what participants prefer when selecting a schedule of interactions distributed over a long duration, and inquire about their scheduling strategies and rationales. In all communication with participants, the study as a whole was framed as assisting fabrication tools, like 3D printers, that intermittently notify the user to ask for assistance. Our study protocol was approved by our institution's Research Ethics Board.

This study took place over multiple days, so we had to create a portable, low-cost system for participants to take to their home or workplace. We used locked and labelled wooden boxes, each containing LEGO pieces and a QR code. SMS notifications with a box ID and lock combination were sent at controlled intervals to prompt an interaction. The QR code inside each box linked to a web page with assembly instructions for the LEGO pieces in the box. Our experiment software recorded when the instructions were retrieved after sending the SMS and when the task was marked as completed on the web page. The participant also had to take a photo of their partially assembled model so we could log when they finished the interaction.

Participants in our study perform study tasks and report their experience in-situ in daily life, rather than in a laboratory environment. Notifications are delivered to each participant's mobile device and session specific questionnaires are presented right after completing a session, which reduces reliance on the participant's long-term memory during data-collection. This setup includes aspects from the "Experience Sampling Method" with mobile devices [46], and we follow related best practices. For example, our study server displays an overview of the study status per participant to the facilitator, which enables providing timely assistance if a participant encounters issues. We also leverage the participant's mobile device to collect observational artifacts in the form of pictures of assembly steps during the tasks.

Each participant completed three *sessions*. During each session they were *notified* multiple times to complete an *interaction*. Each interaction was a LEGO assembly *task* with one or more steps. The number of task steps defines the *interaction complexity*. The number of interactions during a session defines the *interaction density*.

3.1 Task

Participants were asked to assemble three LEGO models in three different 4-hour assembly sessions, each scheduled with 2, 4, or 8 interactions after starting the session. To draw an analogy with 3D printing, starting a session represents starting a print, and the final user interaction represents retrieving and cleaning up the finished print. Since the final interaction is always at the end, a schedule of 2 interactions means a single interaction somewhere between the start and end of the session.

During each interaction, the participants had to place 1, 4, or 12 bricks (or sub-assemblies of bricks). The limited number of pieces to assemble per task provides a soft upper bound for the task duration, but participants are still free to take breaks or delay starting the task if necessary. The specific assembly experience varies between different LEGO pieces, for example when comparing attaching the rubber wheels to placing a sub-assembly of LEGO pieces. Fabrication interactions feature similar variety, for example placing soft press-fit inserts closely resembles attaching the LEGO wheels. All tasks in the study remain qualitatively similar, as they can all be summarized as assembling basic LEGO pieces. The original LEGO instructions of our test models are simple and intended for children 6 years and older. Placing 4 pieces at a time closely matches the original instructions. In contrast, placing 12 pieces at a time far exceeds the number of pieces used per original instruction step and illustration and is sufficient to challenge most users.

We use a LEGO model assembly task for reasons provided earlier: it makes the study feasible and controllable, and building a LEGO model shares characteristics of semi-automated digital fabrication processes. Like a semi-automated 3D printing process, the session progress is paused while waiting for the participant to complete an interaction task. This matches the dependent sequential nature of

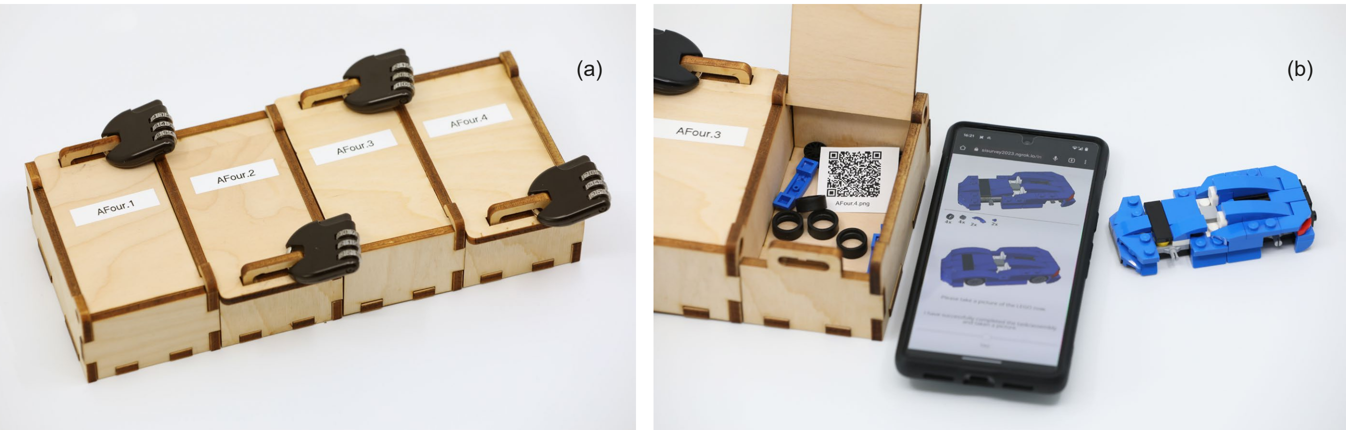

Figure 1: Apparatus: (a) example of individually locked boxes, in this case the 4 boxes are used to control 4 interactions during a session with density level 12; (b) an unlocked box during an interaction task. The QR code leads to a logged webpage with instructions to assemble part of the model using the pieces inside the box.

an intermittent interaction 3D printing process where the printer is paused until the user completes an interaction like changing the spool or inserting a scrap object [48, 49]. Intermittent interaction fabrication systems limit interactions to printing pauses, as modifying the object during printing could disrupt the process, and interacting with running machinery can be hazardous. Similarly, in our study, interactions only become accessible when a box is unlocked after a waiting period.

The number of already opened and remaining locked boxes in a session provides an indication of progression of the study session, similar to comparing the current build height of an ongoing FDM 3D print to the full height of the final model. The physical setup of the study also matches fabrication interactions, such as receiving a set of fabricated parts for assembly after a completed print job. Additionally, some of the parts participants receive are pre-assembled, further mimicking semi-automated processes where the machine performs parts of the process autonomously.

3.2 Participants

We recruited 12 participants through email and word-of-mouth without any specific screening. Regarding demographics: 7 identified as men, 1 as a transgender man, and 4 as women; 6 were between 18-24 years old, and 6 were between 25-34 years old; 6 participants were graduate students, 5 were undergraduates, and 1 was a working professional. They had diverse experiences in fabrication and crafting, from none to expertise in various manual tools and digital fabrication machines. Participant remuneration was $30 and one of the assembled LEGO models.

3.3 Apparatus

To control the timing and availability of LEGO pieces, we employ an array of individually locked boxes (Figure 1a). Each box is secured with a combination lock and labelled appropriately. Additional boxes contain a reminder letter and replacement pieces. Each individual box is large enough to store locks and intermediate assemblies to avoid clutter during the study. A server sends SMS notifications according to the controlled schedule and tracks participant progress. It monitors participant access to web pages to retrieve interaction task instructions, and when they confirm completion after completing each task.

There were three different LEGO models, all race cars, one *green*, one *blue*, and one mostly *white* (Figure 2). They have between 85 and 96 pieces and each can be assembled within 15 minutes. The maximum number of pieces in a model informed the maximum number of pieces used per assembly session. For some conditions, parts of the models were pre-assembled to control the number and complexity of steps in an interaction, and to represent a higher degree of autonomy of the semi-automated process.

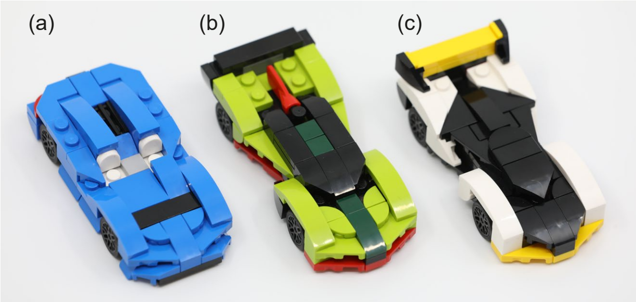

Figure 2: LEGO car models used in study, referred to as: (a) blue; (b) green, and (c) white.

3.4 Procedure

The procedure had three parts: initial setup and instructions, completing the three sessions of assembly tasks, and a final interview.

3.4.1 Initial Setup and Instructions. Each participant met with us to pick up the study boxes. They were briefed about what to expect during the study, and received training how to use a QR code, how to open the combination lock, how to log in to the study server with a password, and how to interpret and select a notification schedule for a session. A reminder sheet with relevant information was placed into a study box. A researcher emphasized that it is up

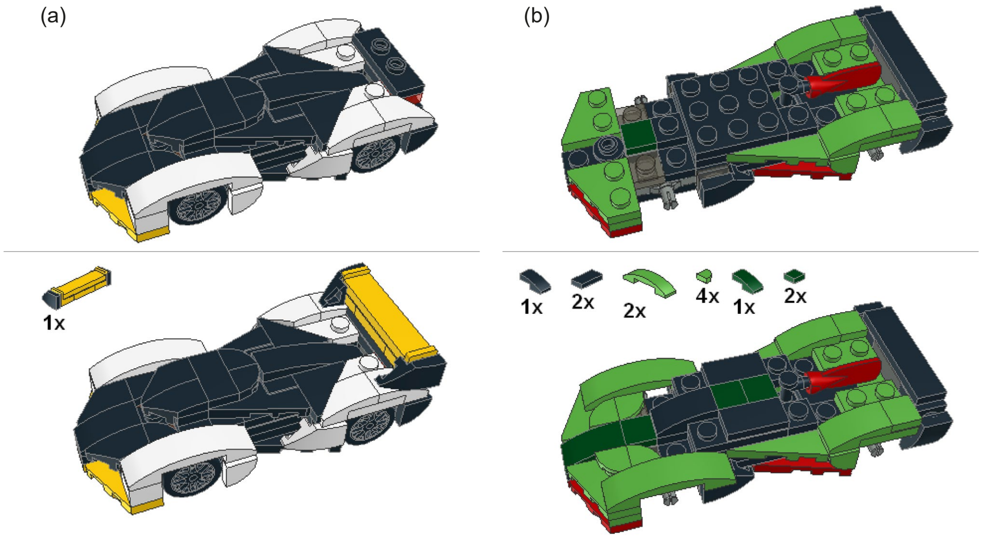

Figure 3: Example task instructions showing current model state at top, and the target state with list of pieces at bottom: (a) a low complexity task adding a single sub-assembly; (b) a high complexity task with 12 individual pieces.

to the participant when to start each session; that each session is scheduled to last 4 hours, but that it is fine to delay an interaction task or to leave the location of the study boxes at their discretion; that they have to complete three sessions to complete the study; and that they can contact the researcher anytime if they have questions. The participant was instructed to set up the study boxes at home or at work, and to leave the boxes there until the final interview.

3.4.2 Assembly Task Sessions. Each participant completed three 4-hour assembly task sessions. Four hours was chosen to represent the duration of a moderately sized 3D print. A paused 3D printer that waits for user interaction does not progress the print and delays completion of the print job. Similarly, in our study, delaying a study task also delays when the session concludes, resulting in session times longer than four hours including variations in delay and assembly time. Most did one session per day and completed the study in under 4 days. When the participant was ready to start an assembly session, they used a QR code to log into the server and select a schedule of interaction notifications[1]. They were given a choice of four pseudo-random notification schedules generated according to the experimentally controlled number of interactions and three constraints for notification distribution. These were: one notification must occur at the very end of the session; the other notifications must not occur within the first 10 minutes or last 10 minutes of the session; and there must be a minimum period of 3 minutes between any two notifications. Enforcing constraints, such as including minimum waiting periods between notifications, better approximates turn-taking with semi-automated machines like 3D printers than fully random schedules. The 10 minute boundaries at start and end approximates startup and cool down times of 3D printers. Using randomly generated schedules with constraints informed by fabrication processes allows observing scheduling strategies specific to fabrication without bias from the authors' scheduling preferences. A new set of four randomized scheduling options was generated for each session. Although participants choose between randomized schedules, the variability of interaction notification timing is bounded by the fixed total session length. The fixed session length means having short intervals between notifications necessitates also having long intervals to compensate, and it limits the maximum time between two notifications to under four hours.

Once the session started, the participant received SMS notifications according to their chosen schedule. Each notification provided a specific box label and a code to open the combination lock. The box contained LEGO pieces and a QR code to open a web page with assembly instructions (Figure 3). The web page also provided a form to confirm they completed the assembly task for the current interaction. In addition, the participant was instructed to take a picture of the current state of the model after completing each interaction. Picture time stamps were examined to ensure that the assembly task was performed when indicated by the web page form. This verified all participants followed the instructions and the assembly schedule. After confirming the interaction task was completed, the number of minutes until the next scheduled interaction notification was displayed. This process repeats until the last interaction task is completed.

After completing the last interaction task in a session, the participant answered a questionnaire with four Likert-type questions about mental demand, annoyance, enjoyment, and sense of contribution. After submitting the post-session questionnaire, the next session was unlocked for the participant to begin when they wished.

3.4.3 Final Interview. After all three sessions were completed, the participant returned to our lab for a final interview. We asked about their general experience, their scheduling preferences, and we conducted an auction exercise to determine their perceived value of each LEGO model. The exercise is based on the variation of the Becker–DeGroot–Marschak method [5] used in The IKEA effect

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[1] The visual presentation of schedule selection is included in the supplemental video.

Table 1: Within and between participants design. The left Latin square counterbalances combinations of density and complexity. The right Latin square is flipped to ensure each model type is assigned exactly once per level of density and complexity, and once per participant. "B", "G", and "W" refer to Blue, Green, and White models.

density (interactions) complexity (pieces)	**2**	**4**	**8**
1	P1	P2	P3
4	P3	P1	P2
12	P2	P3	P1

density (interactions) complexity (pieces)	**2**	**4**	**8**
1	B	G	W
4	G	W	B
12	W	B	G

[28], but adjusted such that the participant is initially gifted the item to allow participation without carrying currency. First, the participant is told they can choose one assembled model as a gift to keep. Then, the researcher offers to "buy back" the chosen model in an auction. After the auction process was explained, the participant was asked to value their chosen model in dollars. This was noted as the model worth, which can be higher than market value. The researcher then rolled a 10-sided die: if the result was equal or higher than the model worth, the researcher bought the model back from the participant for the model worth. Using dice acts as a random number generator as required by the Becker–DeGroot–Marschak method. The procedure ensures that the dominant strategy is bidding the true value associated with the assembled model, as stating a higher value reduces the chance to receive any currency reward, and stating a lower value increases the chance of giving up the model for less than what it is worth. Regardless of the outcome of the auction, the model worth was used as the participant's perceived value of the model. After establishing this baseline, participants were then asked what the remaining two models would be worth to them.

3.5 Design

This is a mixed design study with two primary independent variables: interaction density (as 2, 4, or 8 interactions during a 4-hour session) and interaction complexity (as 1, 4, or 12 pieces of LEGO per interaction task). In the within-participants portion of the design, each participant experienced *each level* of density and complexity over three sessions. During each session, a participant assembles a LEGO model with a total of density × complexity pieces (or sub-assemblies of pieces). In the between-participants portion of the design, *all possible combinations* of density and complexity were explored between subsets of 3 participants. Combinations of the two variables were counter-balanced using a 3 × 3 Latin square (Table 1).

A secondary variable, model, was introduced through the three different LEGO models: Red, Blue, and White. A second flipped Latin square was used to counterbalance model type. This ensures that every participant assembles each of the three different model types, and each model is assembled once with each level of density and complexity between subsets of 3 participants. The order of task density and model type was counterbalanced using the same Latin squares in ascending order of complexity, allowing participants to familiarize themselves with our custom assembly instructions. Using a different model for each assembly session for a participant avoids memorizing assembly steps between sessions. It also maintains the purpose of creating a new item during each session, rather than repeating the assembly of a known item. The inclusion of different models also helps participants differentiate the sessions based on unique visual memories of assembling distinct models. Finally, the inclusion of different models allows gathering additional qualitative insights as participants can more easily delineate between model preferences and process preferences.

Four subjective measures are created by responses to each post-session questionnaire. These were questions with 7 answer options presented equidistant on a number line with Likert-type labels from "Strongly Disagree" to "Strongly Agree" (with a central "Neutral" option). The four questions were:

Mental Demand "The set of tasks was mentally demanding"
Annoyance "I was annoyed by the tasks"
Enjoyment "I enjoyed the tasks"
Contribution "I feel like I contributed to the result"

Three objective measures were computed from timestamps in server logs of user interactions:

Delay Time The interval from SMS notification to scanning the QR code in the study box.
Assembly Time The interval from accessing the instructions to confirming task completion.
Session Time The total duration from session start to completing the last task.

In summary, each participant completed one session with 8 interactions, one session with 4 interactions, and one session with 2 interactions, creating 14 data points for *Assembly Time* and *Delay Time* (168 data points across all 12 participants). In addition, each session generated 1 data point for *Session Time* and 4 data points for subjective measures.

4 Quantitative Results

In this section we present results from subjective measures from the post-session questionnaires, objective timing measures from logs, and the perceived value of the final models. Themes from the post study interviews with an examination of scheduling preferences are presented in the following section.

4.1 Mental Demand, Annoyance, Enjoyment, and Contribution

Figure 4 depicts the distribution of questionnaire responses. More complex interactions, where assembly steps have more pieces, are more mentally demanding, but they also increase the feeling of contributing to the result and increased enjoyment (Figure 4a,c,d).

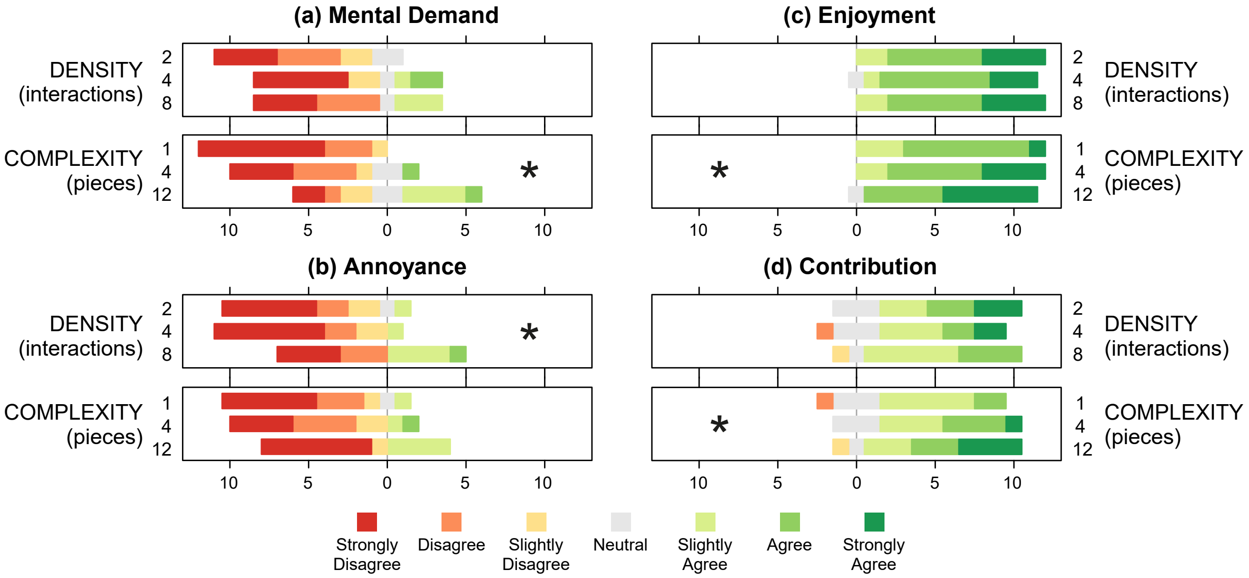

Figure 4: *Mental Demand*, *Annoyance*, *Enjoyment* and *Contribution* by interaction DENSITY, in number of interactions in a session, and by interaction COMPLEXITY, in number of pieces. Significant effects marked with *. Questions for (a) and (b) are negative assertions, (c) and (d) are positive assertions.

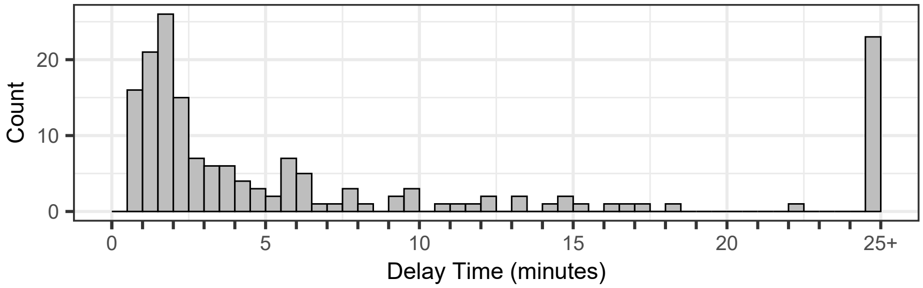

Figure 5: Histogram of the distribution of the *Delay Time* participants took to address each notification.

An analysis of variance based on mixed ordinal logistic regression found effects of COMPLEXITY on *Mental Demand* (χ^2(2, N=12) = 21.05, p < .001), on *Contribution* (χ^2(2, N=12) = 9.27, p < .01) and on *Enjoyment* (χ^2(2, N=12) = 6.02, p < .05). Pairwise comparisons using Tukey HSD indicated that placing 1 piece provided a lower sense of *Contribution* compared to 12 pieces: (Z = 2.88, p < .05). Pairwise comparisons also indicated that placing 4 pieces required less *mental demand* than 12 pieces (Z = 2.36, p < .05). Further pairwise comparisons did not show significant differences between levels of COMPLEXITY on *Enjoyment*.

While a density of 2 or 4 interactions were both comparatively low in *Annoyance*, annoyance increased with 8 interactions (Figure 4b). Three participants specifically commented that 8 notifications were more annoying (P5, P11, P12), but seven participants still reported little to no annoyance. An analysis of variance based on mixed ordinal logistic regression indicated a statistically significant effect of DENSITY on *Annoyance* (χ^2(2, N=12) = 6.84, p < .05). Pairwise comparisons using Tukey HSD did not show significant differences between levels of DENSITY on *Annoyance*.

4.2 Delay Time, Session Time, and Assembly Time

Regarding *Delay Time*, the majority of notifications were either handled in the first few minutes, or after a long delay of more than 25 minutes (Figure 5). This overall trend confirms results from prior work in phone notifications [35], but with an overall elevated *Delay Time* and no recorded *Delay Time* below 30 seconds. Tasks in our study that are handled "immediately" were logged as being handled within 60 seconds to 120 seconds, as unlocking the study box, scanning the QR code, and logging into the study server takes some time, which varies between participants. The shortest *Delay Time* was 46 seconds in our data. Tasks in our study can not be handled directly on the phone and may first require relocating. Study tasks also take longer to handle than typical phone notifications, so they often can not be addressed while primarily engaged in another activity. On average, this leads to an elevated *Delay Time* compared to typical phone notifications. On average, participants took a median of 2.9 minutes of *Delay Time* to address the study tasks, but a much higher mean time of 44.6 minutes (min

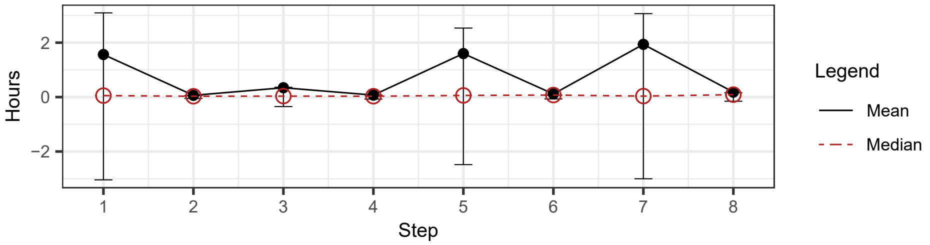

Figure 6: *Delay Time* by interaction occurrence during a session for a DENSITY of 8 interactions. In all figures, error bars are 95% confidence intervals.

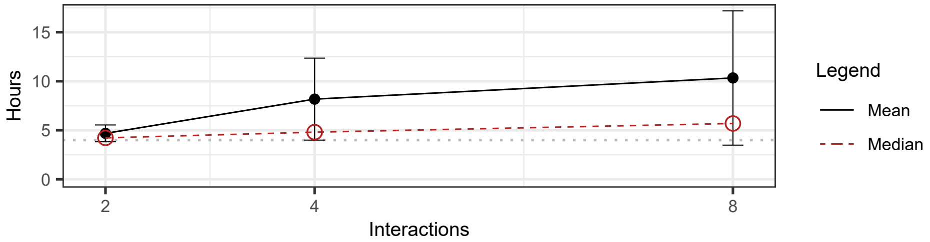

Figure 7: *Session Time* by interaction DENSITY. The dotted grey line shows the minimum session time without any user interaction.

46 seconds, max 17.8 hours, sd 171.3 minutes). The median *Delay Time* for each interaction during a session was consistent (Figure 6), indicating that participants did not grow weary of performing up to eight successive intermittent interactions.

The theoretical minimum *Session Time* to complete a session is 4 hours given how our study was designed. The time to complete a session appears to increase with interaction density (Figure 7). The median session time increases slightly, since every interaction takes time to complete. The effect on mean session time and standard deviation are much more pronounced. In particular, the overall session time is dominated by long pauses, for example, when the participant goes to sleep. The average time to complete a session was 7.7 hours (median 4.7 hours, min 4.1 hours, max 40.7 hours, sd 7.5 hours). The increase in mean session time instead is likely due to a higher likelihood to include long pauses as more interactions occur during a session.

The average *Assembly Time* varied between participants (Figure 8). P10 reported spending a lot of time attempting to fix assembly errors during one session. P2, P5, P8 and P11 participated in the most labour intensive combination of conditions with 8 interactions and 12 pieces per box. P11 noted assembling LEGO for relaxation. The average assembly time across all participants was 3.0 minutes (median 1.5 minutes, min 4 seconds, max 46.4 minutes, sd 4.7). *Assembly Time* also appears to increase with higher interaction COMPLEXITY. The increase was approximately linear with the number of pieces.

4.3 Model Value

Overall, the perceived value of completed models was considerably higher than the value of the model kit itself. Three participants valued at least one of their models as low as $1 (P4, P6, P7), but six participants valued all three models higher than the retail price of $4.99 (P1-3, P10-12). The highest perceived value was $40 (P1). The median perceived value of a model was $8.25 (average $9.31, sd $7.58). This is 65% above retail price, which closely matches the 63% increase in valuation determined in the “IKEA effect” [28]. Eight participants chose to keep the green model, two chose blue, and two chose white. Nine participants said they chose the model to keep based on a preference for the model itself, which may have been influenced by the building process. Three participants explicitly chose the model based on the process, picking the model where they placed the most pieces and that was most challenging to assemble (P2, P10, P11).

5 Qualitative Results

We analyzed audio transcripts and notes from participant interviews, which lasted on average 45 minutes, using techniques from Thematic Analysis [6]. We first identified meaningful statements made during the interviews and clustered related statements together. During the analysis, participant data was added using constant comparison while focusing on similar and conflicting experiences. We identified and developed five main codes by looking at the structure of mapped thematic clusters. We present and describe codes organized by topic below.

5.1 Enjoyment Through Engagement

All participants generally enjoyed the study and the LEGO assembly task. Various sources of enjoyment are directly related to the participants level of engagement with the tasks.

Challenge fosters engagement. Participants overwhelmingly enjoyed the complexity that came with assembling more pieces (P3, P4, P6-11). They described it as an interesting challenge (P1), a puzzle (P5, P12), and overall, as the most enjoyable. P5 called the tasks

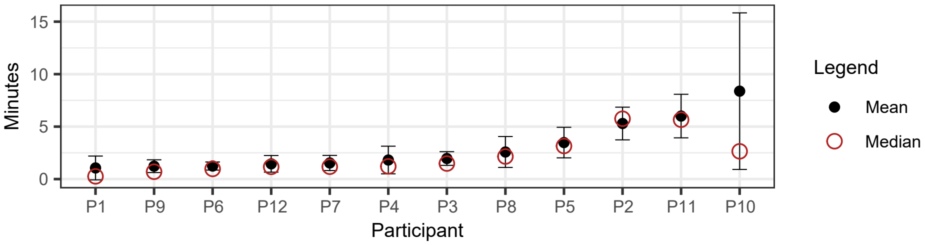

Figure 8: *Assembly Time* per participant.

a "*3D manipulation challenge.*" One participant was even adamant that they had performed only half as many of the most complex tasks than they actually had done, suggesting time passing quickly due to elevated engagement levels (P3). This participant even preferred when there were identically coloured pieces and asymmetric assemblies for increased difficulty.

Overcoming challenges bolsters accomplishment. Being fully engaged in a challenge seems to stimulate feelings of accomplishment after completion (P10, P11). Two participants felt accomplished for correcting mistakes from a prior interaction (P4, P9) and one participant described completing the complex instructions as "*defeating a Dark Souls boss*" (P7).

Manual tasks evoke engagement. Participants appreciated the dexterous tactile manipulation experience of assembling LEGO, stating it engaged a different part of the brain than passive activities like watching videos (P1, P4, P5). Participants also found tangible satisfaction in putting on the pliable tires or continuing to play with the completed models (P6, P8, P9, P11). Two participants however struggled with handling small building blocks (P2, P7). P7 described the tasks as "*tinkering with small pieces, with big hands.*"

Partitioned tasks enable offline engagement. Spreading the assembly process out over a longer period of time allowed participants to think about the tasks while not actively engaged in an interaction. Three participants noted enjoying the anticipation and trying to predict the next steps (P9-11).

5.2 Enjoyment Through Progression

Another source for enjoyment during a session was experiencing progress as each interaction task was completed. While partitioned the assembly seemed to heighten this sensation, it also delays the most gratifying part of a creation process, completing the last step.

Creation tasks tangibly track progress. Since the assembly is a physical item, the state of the item provides a tangible progress record. Participants commented that it is enjoyable to see an assembly come together and to observe the impact each step makes (P1, P7). Participants especially appreciated the final steps (P2, P5, P6) and likened them to "*cutting the ribbon*" or "*putting the cherry on top*" (P4).

Partitioning delays gratification. Given that the last step is the most enjoyable, many intermediate steps distributed over a long time can feel like delaying "the finish line" (P4, P11). One participant was so motivated to avoid this delay that they admitted to trying to cheat the system by (unsuccessfully) guessing the code for the very last box (P8).

5.3 Task Partitioning is Both Loved and Hated

Participants describe task partitioning as helpful and following the process can feel rewarding. However, excessive partitioning into too many small interaction tasks was the main source of annoyance.

Partitioning processes promotes completion. Five participants found the segmented approach helped them finish a session, as attempts to tackle the entire assembly have been overwhelming or increased hesitancy to even start (P7-10, P12). Due to partitioning into small interaction tasks, one participant was able to fit the overall assembly into a tight schedule (P9). One participant said that the study setup was "*more engaging, more active and more accountable than a to-do list.*" (P7), and the study setup helped complete successive tasks much faster than using a to-do list. Partitioning was also credited with helping handle task complexity, since it enforced a systematic approach and provided clarity where to start (P7, P8, P10, P12). One participant estimated that performing the same assembly in one go would take three times as long (P7).

Notification timing matters. Three participants noted that receiving multiple interaction notifications within a short period of time can be irritating (P5, P11, P12). On the other hand, long periods between notifications can feel "*like a slog*" (P4). Waiting is harder when not otherwise occupied. Only participants who performed the study at home, rather than at work, lamented long time intervals between interactions (P3, P4, P6, P10). Participants who noted a preference, said 2, 3 or 4 notifications during a 4 hour making process was ideal (P5, P6, P9, P10), explaining that fewer interactions create pauses that are too long or offer "*too little involvement*" (P9).

Every interruption should be worth it. Two participants complained that for interactions with minimal complexity, waiting for notification to do the next interaction was "*not worth it*" (P1, P10). Two participants suggested that knowing the goal of the creation task provided additional motivation (P1, P7). Notifications for more complex interaction tasks were met with excitement (P10, P11), even described as a "*dopamine rush*" (P9). The interaction tasks in our study were mostly considered not annoying since participants felt they served a purpose (P1, P4-6, P10, P11). Placing mirrored pieces in consecutive tasks was noted as an exception, as placing them felt repetitive (P3, P12).

Ongoing processes can be stressful. Some participants felt a strong commitment to complete each step as soon as possible to avoid compounding delays (P1, P2, P12). A large number of interactions can increase the perceived urgency of the tasks, which can lead to stress. Due to travel plans, a participant felt the need to "*drop everything*" to respond immediately and avoid further extending the session (P5). Another participant reported taking assembly pieces to the bathroom to save time (P6). Participants were largely unconcerned with assembly errors, unless they blocked further progress. Our study setup did not offer the option to restart a session to recover from a previous assembly error. One participant felt stressed when they continued the assembly in an error state that they failed to fix without access to the previous set of instructions (P10).

Partitioned tasks means following a schedule. Some users partially relied on "mental math" to follow their session schedule (P6, P9, P10), or relied on checking their phone regularly due to all notifications being silenced (P12). Forgetting about performing interaction tasks can be annoying and of course introduces delays in the overall assembly progress. Very long breaks between interactions make forgetting more likely (P12), and two participants noted that 3-hour long breaks between interactions were too long to remember (P9, P10). Other participants praised how the phone notifications offloaded the mental effort of remembering to follow a schedule (P7, P8).

5.4 Opposing Strategies when Picking Schedules

The majority of participants were satisfied with their chosen schedules and felt a list of four schedule options was adequate. One participant desired additional options (P9), but noted many options can also lead to "choice paralysis". Three participants said they were content selecting a schedule randomly from the options, for example simply selecting the first schedule option (P1, P2, P8). They still discussed alternative schedule selecting strategies when asked. Participants mainly relied on two opposing strategies discussed below, while also considering scheduling around real world events.

Clustering interactions felt easier. Eight participants used a schedule selection strategy of picking the option with the most clustered interaction tasks, preferably at the start or end of the schedule. The reasoning given was this kind of schedule minimized the mental load of context switching. Six participants specifically preferred clustering interactions at the start of the session. A common reason was to not forget about the whole assembly and more quickly get a sense of what they are building.

Spreading interactions can be useful. Five participants preferred an opposite scheduling selection strategy where they picked the option with interactions spread most evenly. They found shorter intervals between interactions distracting, instead preferring longer gaps close to an hour (P2) or a more "*workable*" interval of about 45 minutes (P12). One participant looked for the regularity of "*good, logical breaks*" in the most uniform distribution option, but also favoured schedules where 2 or 3 interactions were clustered within 20 minutes (P5).

Scheduling around events overrules other strategies. Accommodating specific events, primarily meals, was noted repeatedly as an exception to other schedule selection strategies. When applicable, a schedule that worked around known real world events that occurred during the session time was always the top priority (P1, P2, P12).

5.5 Participation can Increase Desirability and Perceived Value

Four participants explicitly stated that a model's worth was proportional to the time spent building it, referring to models assembled with higher density and complexity (P2, P11, P12) and higher complexity in particular (P4). In general, the model with the highest monetary value was the one the participant chose (i.e. the model they *desired*), but not always. Two participants chose to keep a model that they did not assign the highest value. P10 chose a model they had assigned a low value due to assembly errors, but they wished to rebuild it as a challenge after the study. P4 chose a model to keep that depicted a real car they were a fan of, even though they valued another model at a higher monetary value, which they "*had more fun and spend more time building*" in the highest complexity condition.

Participation threshold for ownership. Six participants noted some lack of ownership in a model's assembly due to a condition with low complexity and density (P4, P5, P7-9, P11). They characterized the assembly process as "*repairing*" rather than "*building*" when placing only one piece at a time (P5), or as "*playing with someone else's toy*" (P11). A participant noted that they would pay more for a kit than for a pre-assembled model they "*didn't build*" (P8). This sense was only shared by half of the participants, and only in the lowest complexity and density conditions. Beyond minimal participation in the assembly, such as merely placing two LEGO bricks on an otherwise complete model, even marginal participation was sufficient to instill a sense of ownership, and the models built in the lowest complexity and density conditions were on average still valued above market value.

6 Discussion

We discuss our results and how they can inform designing intermittent interactions in the context of fabrication systems. We also propose a method to predict or generate preferred schedules heuristically.

Using a single, simple intermittent interaction during a fabrication process has been a common approach in prior work. Our results confirm that users do not find this interaction pattern annoying or mentally demanding, and that for some users even this minimal participation is sufficient to feel that they contributed to the outcome. Surprisingly, we found that there is no strong negative connotation of performing additional or more complex intermittent interactions, and we found that the majority of participants did not feel annoyed at all across the full range of densities and complexities we explored. This result is unexpected, since systems that are designed for multiple intermittent interactions are rare, and can inform the design of future semi-automated systems.

Participants generally felt they contributed to the outcome of creating a model, and the perceived model value was also generally much higher than its real market value. The increase in perceived value in our results matches the findings of The IKEA effect [28], demonstrating that the effect persists when interactions are spread out over a long period of time. Our qualitative results also suggest that the effect scales with conditions that foster engagement, such as highly complex tasks that challenge users and provide a sense of tangible progress during an interaction, rather than with the time spent interacting directly.

Limitations. Results generated in a controlled study may not be directly comparable to real world experiences. For example, the study boxes unlock based on a timer, rather than actually waiting for an ongoing physical process to complete. This may lead to users feeling a lack of justification for the waiting times during the study. Waiting for an artificial or unjustified reason is likely a worse subjective experience than waiting for actual semi-automated fabrication progress. The abstracted tasks of our controlled experiment still show typically low annoyance, and real world annoyance can be expected to be similar, or lower, if the waiting periods feel more justified. Participants were able to repeat prior assembly steps as a form of error recovery, which may not be possible during digital fabrication. However, without immediate access to prior assembly instructions, error recovery in our study still proved difficult.

The interaction complexity in our study was limited, but the high complexity condition in our study was sufficiently difficult to challenge users. Even more complex interactions could lead to high failure rates that are undesirable in long processes like semi-automated fabrication, and outside of creative applications, intermittent interactions in prior fabrication systems tend to be simple.

The choice of assembling LEGO models during the study tasks lead to overall high levels of enjoyment. The average enjoyment may be elevated compared to real world applications, but our results still show that tasks with varying levels of complexity can significantly change how much users enjoy them.

Applications to Fabrication. Our results find application in semi-automated fabrication systems similar to those listed in the related work, for example, to justify extending user involvement beyond a single interaction. Our guidelines inform the design of user interactions and interaction limits, and could help build systems that support and reduce the effort of intermediate fabrication techniques, such as inserting captive nuts, magnets, and other mechanical parts [11, 17, 21, 40], which require manual pausing or slicing adjustments. Scheduling interactions to match the timing of existing, necessary interactions, such as replacing filament spools, could reduce the perceived cost of interactions overall.

Some manual tasks, such as switching between filament colours, can be automated by more complex fabrication machines. Some basic intermittent interaction tasks may eventually also be able to be handled automatically using more complex hardware. These additions increase the mechanical complexity and costs of machines, making them less accessible. Additionally, many intermittent interactions require high levels of precision and dexterity that are hard to automate, even with specialized hardware, so user assistance is likely to remain relevant in the future.

Applications beyond Fabrication. There exist other interaction patterns that share similarities with intermittent interaction, commonly found in activities that rely on physical processes. The insights from studying intermittent interaction may find application in other domains, such as software for IoT devices, or AI assistants that help manage household automated appliances, such as a laundry machine or an oven.

6.1 Guidelines

Based on our findings, we propose guidelines for designing systems that use intermittent interaction.

Minimize annoyance, not effort. Fewer, more complex interactions are both more rewarding and less annoying. Avoid repetition, like performing the same operation twice for a symmetric process. Less complex user interactions, more comparable in difficulty to placing 1 LEGO piece than placing 12 LEGO pieces at a time, may be insufficient to instill a sense of ownership. Avoid using more than 4 interactions in a 4-hour process, and more generally, using more interactions than the number of hours in the process duration.

Allocate complexity. More complex tasks feel impactful and engaging to users. Interactions that are too simple can feel like wasted effort. Provide user options to adjust task complexity, such as setting an upper limit on interaction complexity, which also helps to avoid errors that can lead to frustration.

Manage time expectations. Only inform users of upcoming interactions when they are imminent or urgent. Time periods between interactions less than 10 minutes are typically considered acceptable. To mitigate a sense of prolonged waiting for interactions scheduled hours later, consider only informing the user when the task becomes available or shortly prior.

Design purposeful notifications. Clearly articulate the purpose and the value of intermittent interaction as part of the overall process. A sense of contribution requires knowledge of what the user is working towards, or what their efforts accomplish. Consider including information such as material savings in communications with the user.

Mitigate mistakes. Prioritize error prevention and recovery for physical interactions. Use constraints to prevent invalid user actions (e.g., keyed inserts to constrain insertion orientation). Provide redundancy in instructions to simplify verifying the success of the interaction (e.g., add a second angle view for visual instructions). If possible, allow mistakes in previous interactions to be corrected (e.g., a break-away cover allows flipping magnetic inserts later).

6.2 Guideline Application Example

We apply these guidelines to the Substiports intermittent interaction fabrication system [49] to illustrate how they can inform design. Substiports replaces printed support structures with manually inserted objects. The current system assigns a penalty to candidate insertions based on interaction complexity, favouring multiple simple interactions. Following the *minimize annoyance, not effort* and *allocate complexity* guidelines, a lower complexity penalty should be used, perhaps even a negative penalty (i.e., a gain), to promote fewer, but more complex interactions. Substiports is built into the slicing process and uses beeps and the built-in printer display to inform and instruct users. Based on the *manage time expectations* guideline, the remaining time until the print is finished should be modified (e.g., using G-code commands) to instead display the time

Effort Minimization	
Clustering Interactions	Participants preferred grouping interactions closely together to minimize the cognitive load from disruptive context-switching.
Anchoring at Start and End	Interactions anchored around forced start and end points reduce mid-process disruptions.
Front-Loading	Clustering at the start preserves engagement momentum while in the task-oriented mindset of starting the process.
Extended Intervals	Clustering interactions around the edges of the time frame incidentally schedules long, uninterrupted periods that allow accomplishing more demanding work.
Expectation Management	
Uniform Distribution	A consistent spread of interactions allows for better anticipation and planning around them.
Pomodoro Alignment	Interactions can be used to implement a 'Pomodoro'-style work method, breaking up work into focused intervals.
Event Scheduling	
Considering Real World Events	Users prefer that interactions are not scheduled at the same time as real life events, like lunch, to avoid disruptions during those periods.
Events are Contextual	Scheduling around events required contextual information, which can be entered manually, or for example by incorporating calendar information.
Mental Overhead Minimization	
Random Selection	Users may choose random or first-available schedules to eliminate the cognitive burden of planning.
Avoiding Overthinking	A quick selection allows users to commence interactions more swiftly and negates the need for detailed forethought.

Table 2: Objectives for planning intermittent interaction schedules

remaining until the next user interaction. Considering the *design purposeful notifications* guideline, a message noting the amount of printing material saved could be displayed alongside the instructions during any printing pause to help convey the value of each interaction. Finally, Substiports makes use of height-variable inserts to replace support material sections. An issue, such as printing material not adhering to the inserted object, can have severe effects, including causing the entire print to fail. Following the *mitigate mistakes* guideline, the system could be adjusted to create a buffer of a few layers of printed support on top of inserted height-variable objects. This would give users a period of time to correct issues like poor adhesion by fine-tuning the height of the insert.

6.3 Formalized Schedule Preferences

Scheduling strategies are personal and varied. We formalize the primary objectives leading to the scheduling strategies participants used in Table 2. Participants typically focus on either minimizing effort, or on making interactions easier to manage and work around them by spreading them evenly throughout the process duration. Scheduling around events supersedes other strategies where necessary, but requires additional contextual information.

6.4 Predicting Preferred Schedules

We built heuristics that approximate the two dominant interaction scheduling strategies by encoding the *effort minimization* and *expectation management* objectives we found in our interview analysis listed in Table 2. The heuristics can be used to evaluate or generate schedules that can predict the user selections in our study well. A binary preference value is required to choose which of the two heuristics to use, which can be set simply by letting the user choose between two indicative sample schedules.

Recall that three of our participants said they selected schedules randomly to avoid making a decision. To support this user group, we recommend providing fully automated schedules based on preference settings. Other users can also benefit from strong default suggestions, for example by simply accepting a suggested schedule instead of searching through a list of options, which *minimizes mental overhead*.

To evaluate the accuracy of predicted schedules, we count the number of times the heuristic function selection matches participant selection. A match describes selecting the same schedule out of four options that were presented at session start. Note the 9 data points from participants who said they selected randomly were removed as outliers in this evaluation. After selecting a user preference to use or avoid clustering based on interview transcripts, our suggested approach matches user selection in 21/27 cases (77.7 % accuracy), compared to 40.0 % accuracy when selecting the better out of two functions that select randomly.

Our approach uses two heuristics to evaluate schedules, *cluster early*, which supports the *effort minimization* objective, and *avoid short intervals*, which facilitates *expectation management*. The *cluster early* heuristic counts and maximizes the number of scheduled interactions that occur within 15 minutes after session start and after one another. The shortest total time length of this early cluster is used as a tie breaker. If there are no intervals between two successive interactions that are 15 minutes or less, the shortest interval length within the schedule is used instead of 15 minutes. The *avoid short intervals* option counts and minimizes the number of intervals that are shorter than the expected interval length if interactions were distributed uniformly. A measure of how much shorter these intervals are than expected is used as a tie breaker.

The results of these heuristics may still be superseded to accommodate *event scheduling* where appropriate. For example, offering additional preference options, such as avoiding interactions during lunch time, may further increase prediction accuracy and allow systems that make use of intermittent interactions to better lift the burden of choosing a schedule off of the user.

6.4.1 Scheduling Application Examples. Our heuristics assign a fitness value to each schedule. Systems that numerically evaluate and compare different interaction options can use this value to take scheduling into account during comparison. For example, the Substiports system [49] performs an optimization to maximize support material savings and minimize the number of interactions. Including the heuristic fitness value during optimization could improve how well the interactions match user scheduling preferences. Note that Substiports makes adjustments to a slicing result, demonstrating that intermittent interaction schedules can be chosen after primary fabrication considerations, such as build orientation.

Scheduling can be considered whenever multiple options for user interactions are available. For example, using magnetic inserts or captive nuts of different sizes, or adjusting their positioning, can change when the insertions occur without loss in functionality. The choice between different options could be made based on which choice best fits the user's preferred schedule. As another example, Medley [7] offers a "library of embeddables" that groups inserts based on the functionality they provide. Choosing from the set of inserts that provide the desired functionality could be optimized to avoid undesirable interaction schedules.

7 Conclusion

We investigated how people perceive intermittent interactions with manual assembly tasks over long durations through a multi-day study. LEGO model assembly was used to represent more general kinds of interactions, and the context of 3D printing informed the design of the study and user interactions. Placing LEGO blocks requires some manual dexterity and high precision without being physically straining. These qualities match many types of interactions with digital fabrication systems and intermittent interactions within that space. However, our findings may not be applicable for certain interactions, for example tasks that are highly physically demanding. On the other hand, many tasks outside of the immediate context of digital fabrication, such as household tasks and handling appliances have a similar level of physical demand, and our findings may extend to other domains. Future work could explore interactions based on tasks of other turn-taking scenarios like traditional crafts and arts or revising documents, or shorter time frames that better match other types of digital fabrication, like laser cutting.

Our results provide evidence that intermittent interaction is generally acceptable for long duration creation tasks such as personal fabrication with a semi-automated machine. We found that scheduling strategies are diverse, but often predictable with simple heuristics. Using our guidelines, we hope future designers feel more justified and informed when integrating intermittent interaction into semi-automated fabrication systems and extend existing workflows, perhaps even fostering more meaningful engagements with technology.

Acknowledgments

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