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Pozo Arcos, B.; Dangal, S.; Bakker, C.A.; Faludi, Jeremy; Balkenende, A.R.

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Faults in consumer products are difficult to diagnose, and design is to blame: A user observation study

Beatriz Pozo Arcos *, Sagar Dangal, Conny Bakker, Jeremy Faludi, Ruud Balkenende

TU Delft, Building 32, Landbergstraat 15, 2628CE, Delft, the Netherlands

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ABSTRACT

The process of fault diagnosis is an essential first step when repairing a product: it determines the condition of the parts and identifies the origin of failure. We report on how product users go through the process of fault diagnosis in consumer products and the influence of design features on this process. Two groups of 12 participants were asked to determine the fault in a defective product we supplied; the groups differed in their self-reported repair expertise. Four types of products were used for the study: a vacuum cleaner, kitchen blender, radio CD player, and coffee maker. During the experiment, the participants were asked to think aloud to explain their actions and understandings. Afterwards, they were interviewed regarding their experience. The results from the verbal and video analysis provided input for an updated framework of the diagnosis process, describing user actions at each diagnosis stage. Furthermore, we show that the way a product is designed and constructed (the positioning, accessibility, and visibility of relevant product components) has a significant influence on the success of the fault diagnosis. An important factor is user experience: product use facilitates signal recognition, while repair expertise facilitates disassembly. However, user experience is still less influential than the product's design. Based on these findings, we propose a set of design guidelines to facilitate the process of fault diagnosis in consumer products.

1. Introduction

Repair practices can positively contribute to the decoupling of consumption from resource use in a circular economy (Stahel, 2006). Repairing instead of replacing products has the potential to increase resource efficiency and decrease the environmental impact resulting from premature product replacements (Bakker et al., 2014; Stahel, 2006; Truttmann and Rechberger, 2006). Consequently, improving the reparability of consumer products is one of the measures proposed in the European Commission's Circular Economy Action Plan to reduce waste and consume more sustainably (European Commission, 2015). Moreover, there is a growing societal interest in repairs stirred by consumers and grassroots associations which aim to repair their products (Terzioğlu, 2021).

Repairing a product requires identifying the component at fault (fault diagnosis), disassembly to make the component accessible, repair of the defective component, followed by product reassembly (Cuthbert et al., 2016; Pozo Arcos et al., 2018). Without the process of fault diagnosis, subsequent repair steps cannot be taken. Easy diagnosis could improve users' confidence about what needs to be repaired and motivate them to repair instead of replacing their product. Easy and effective fault diagnosis can reduce intangible costs influencing the repair-or-replace decision: travel and waiting times, user frustration between breakdown and the uncertainty of the repair outcome (Brusselaers et al., 2019; Sabbaghi et al., 2016).

While there are studies on the process of fault diagnosis, it is unclear how designers can create products that can be successfully diagnosed by end users. Design guidelines addressing the diagnosis process are scarce, and mostly focused on technicians and complex, industrial products (Go et al., 2015; Pozo Arcos et al., 2018; USA Department of Defense, 1988). Den Hollander (2018) distinguished 16 design principles relevant for facilitating repairs in consumer products. However, it remains unexplored to what extent these design principles relate to the diagnosis process. Similarly, recent studies investigating the diagnosis of appliances have not addressed the influence of design for the diagnosis process and are focused on how technology can facilitate it instead. For instance, recent studies aim to improve product-specific algorithms and methods for fault detection in home appliances (Baek et al., 2020; Jiang

* Corresponding author.
E-mail address: b.pozoarcos@tudelft.nl (B. Pozo Arcos).

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et al., 2018; Marcu et al., 2017). Other studies focus on integrating home appliances to smart networks to facilitate their service by using technology like the internet of things, cloud computing, and machine learning to monitor and diagnose them (Bhavana, 2020; Rashid, 2019; Suresh, 2019). Moreover, most academic studies on the repair process focus on product disassembly (De Fazio et al., 2021; Mathieux et al., 2018) and the development of repair indicators (measuring the reparability of a product) (Bracquene et al., 2018; Cordella et al., 2019; Flipsen et al., 2019). In some of these studies, fault diagnosis is mentioned as a necessary precursor to any successful repair, but the process and its design remain under-investigated. Furthermore, academic studies investigating the user's perspective on repairs are focused on consumer attitudes to repair, and do not study the practice of diagnosis and repair in appliances (Jaeger-Erben et al., 2021; Rogers et al., 2021; Terzioğlu, 2021). Thus, the available literature is insufficient to provide guidance for designing easy-to-diagnose appliances: the product-user interaction is insufficiently understood, and existing guidelines on design for diagnosis are lacking for household appliances.

Our previous study (Pozo Arcos et al., 2020), developed a model of the fault diagnosis process and identified product design features that have an influence on the time and expertise required for fault diagnosis. In this study, we take a next step towards a more detailed understanding of the process of fault diagnosis for repair. The aim of our paper is to investigate how users with different repair skills carry out the process of fault diagnosis on consumer products and how this is affected by a product's design and the end-user's repair skills. Data were collected in a user observational study in which participants with different self-reported repair experience performed the process of fault diagnosis in four consumer products. In this study of the process of fault diagnosis, we add to the current, technology-focused academic perspectives by including user perspectives on fault diagnosis. In this way, we contribute to the body of knowledge of design for reparability by providing an initial set of design guidelines to facilitate user fault diagnosis.

In Section 2, we present the theoretical framework that guided our analysis. Section 3 describes the methodology, and in Section 4 we present the results of our analysis: a description of the diagnosis process followed and the influence of repair skills and design features on the process. In Section 5 we discuss and compare the results with preliminary findings, yielding an initial set of design guidelines for easing the process of fault diagnosis. In the final section, we present our conclusions.

2. Fault diagnosis model and analysis framework

In this section, we present the theoretical framework that guides our analysis. We start by introducing the diagnostic steps we expect participants to follow based on the framework of the diagnosis process. We then present a set of search strategies that participants could use to find faults in the products.

2.1. The diagnosis process

The process of fault diagnosis determines the defective component of a malfunctioning product in three steps (Pozo Arcos et al., 2020) (Fig. 1): fault detection identifies a functional malfunction in the product; fault location determines the possible causes of the failure; and, fault isolation pinpoints the component at fault, thus diagnosing the product.

The process starts by detecting symptoms of malfunction in the product. The symptoms provide different types of information that help users locate the faults. These symptoms, together with symptom-to-cause knowledge, product information, and the product's history of use and repairs are used to determine the possible causes of failure (possible defective components) and corrective actions. Thereafter, users isolate the fault by checking or testing components suspected to be at fault.

2.2. Strategies for fault diagnosis of consumer products

Diagnosing a fault in a product is most likely comparable to any human problem-solving mechanism. Jonassen and Hung (2006) and Angeli (2010) refer to the diagnosis process as a complex reasoning process similar to solving a problem. Therefore, we used recent literature on problem-solving strategies to understand what can be expected from participants during the diagnosis process.

As Whalen (2019) describes, solving a problem consists of devising actions to move from an existing situation to a desired one. It is a cognitive search through a large set of possibilities that requires understanding and is guided by heuristic knowledge (Robertson, 2017; Simon et al., 1987). Similarly, fault diagnosis requires an ability to combine repair experience and technical knowledge to relate symptoms to possible problems (Kluge and Termer, 2017; Morris and Rouse, 1985; Wasserkrug et al., 2019).

Robertson (2017) describes two main strategies people use to search for a solution (Robertson, 2017): strong and weak strategies. Strong

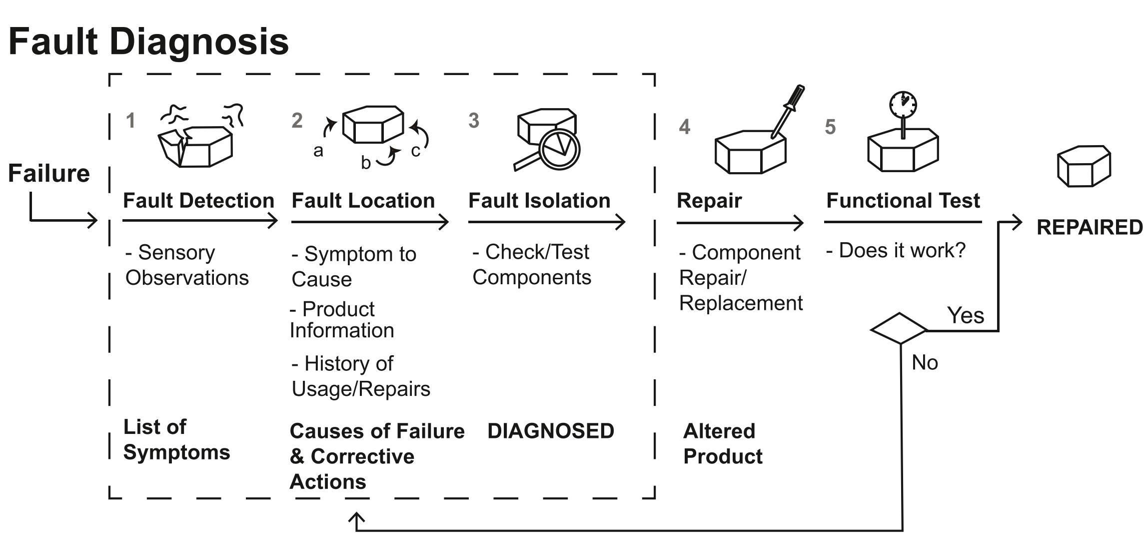

Fig. 1. Model of the process of fault diagnosis by product users (Pozo Arcos et al., 2020).

strategies are domain-specific, are guaranteed to get a solution, and are used when the solver knows how to go about solving the problem. Weak strategies are general-purpose strategies that solvers use when they do not know what to do directly to solve the problem. Within this latter category, the author recognises two different types: hill climbing and means-end analysis. "Hill climbing" only applies when there is some way of determining whether the solver is getting closer to the goal. Means-end analysis involves breaking a problem into sub goals; solving each sub-goal should eventually solve the whole problem. Duris (2018) defines "blind search" as a type of weak strategy whereby all potential solution candidates are checked randomly. Jonassen and Hung (2006) add that novice troubleshooters tend to go for low performance strategies, while expert troubleshooters use the recall of historical information as a strategy for fault diagnosis. In Robertson's terms, this would mean novices would go for general-purpose (weak) strategies and experts would follow domain-specific (strong) strategies. Applying one strategy or the other provides feedback to the solver about the results, and consequently, the solver may change the initial strategy, thereby applying multiple strategies in the search for a solution (Patrick, 1993; Robertson, 2017).

Collectively, these studies indicate that, when diagnosing a product, we can expect participants to follow the diagnosis steps in the order presented in Fig. 1, and adopt strong or weak search strategies depending on repair experience and technical knowledge. Their heuristic, product-specific knowledge gained in everyday life by using, maintaining, and repairing a similar product could be relevant for diagnosis. Therefore, we can expect that those participants with more repair experience will follow more directed ('strong') search strategies. Moreover, we could expect users to follow more than one strategy if the results of an initial strategy do not lead to identifying the defective component.

3. Method

3.1. The think aloud method

We used the think aloud method to conduct the study. This is a method used in studies designed to understand users' cognitive processes when carrying out a task (Hoppmann, 2009; Whalley and Kasto, 2014). It has been shown to be a useful and reliable technique because it poses minimal interference with the participants' reasoning. Participants are instructed to speak their thoughts as they work on problems and do so as if they are "speaking to themselves". No explanations for their reasoning or their feelings are required, which allows eliciting the tacit knowledge of the participants (Crandall et al., 2006).

3.2. The participants

In order to recruit participants, a questionnaire was sent to a participants of a university-based research panel, who live within a radius of 30 km from TU Delft. This panel includes 1000+ volunteers (52.6% male and 47.4% female) aged 21–70 (average age 59), with different education and professional backgrounds, recruited by TU Delft over the years. They were asked about: (a) their experience using standard tools for repair: a plier, a screwdriver, a wrench, and an Allen key; and (b) previous experience repairing different durable goods: bikes, small and large household appliances, and electronic products. The participants specified how often they had repaired the durable goods from 5 options: never, once, a few times (2–5 times), several times (more than 5 times) or "at a professional level". From the responses (n = 273), we selected two groups of 12 participants based on their self-declared repair experience, their availability to participate in the test, age, and gender. We recruited (a) "Users with repair experience": users who claimed to have repaired appliances 2–5 times, and (b) "Users without repair experience" i.e. those who claimed to never have repaired an appliance, but knew how to use standard tools. The two groups had similar characteristics regarding age (45–65 years), repair experience, and gender ratio.

After gaining approval from the ethics committee at TU Delft, we proceeded inviting the 24 participants to the TU Delft facilities in February 2020 where they signed a consent form and were asked to diagnose a malfunctioning, consumer product while thinking aloud. The observations were carried out in a laboratory setting and lasted 40 min or until the participants diagnosed the product. Immediately after, the participants were briefly interviewed about their experience. Both the observations and interviews were video recorded.

3.3. The products and the faults

Four small consumer products (blender, vacuum cleaner, coffee maker, and a radio CD player) were chosen based on the criteria:

- The products include a variety of design features that could influence the diagnosis. Using Pozo Arcos et al. (2020), we selected products with different features to access the components, to provide feedback to users, to interchange components, and with different types of functional modules.
- The products cost less than €150 each due to the focus on small, common consumer products and budget restrictions.
- The products can be disassembled and reassembled multiple times without damage, so that they could be used repeatedly during the experiment.

A controlled fault was introduced in each of the products (Table 1 and Fig. 2) based on the criteria:

- The fault would cause symptoms frequently occurring in consumer products. Symptom frequency was extracted from iFixit's forum of technical repairs (iFixit, 2019) and the Repair Café's report on frequently repaired faults in 2019 (Repair Cafe International Foundation, 2020)
- The fault was provoked in an internal component to observe the participants interacting with a large diversity of design features and components.
- Each fault would provoke one of the different type of symptoms described in Pozo Arcos et al. (2020): under-performance, absence of response to commands, abnormal inbuilt signals, and designed signals. The symptom of intermittent failure was excluded because it would be hard to replicate and control.

In the radio, we introduced two faults: discharged batteries and a disconnected cable plug; the participants could only diagnose the second fault after diagnosing the first one.

The room set up for the experiment is shown in Fig. 3. Three video cameras were placed in the room: two on each side of the walls pointing towards the interaction space, and one action camera worn by the participant during the experiment. Microphones were suspended from the ceiling.

3.4. Procedure of observations

Each participant diagnosed one randomly selected consumer product. In total, each product was diagnosed by three participants from the group with experience and three from the group without repair experience. The participants were given a maximum of 40 min to find the defective components, however, to avoid stressing them, this was not communicated. They were able to use tools and the user manual; but only upon request.

The observations started by showing participants how to perform a common task with a fully functional product: a) make a smoothie with the blender, b) play a CD in the radio/CD player, c) make a cup of coffee with the coffeemaker, and d) vacuum rice from the floor with the

Table 1
Overview of the consumer products used and the faults provoked in them.

Product	Model No.	Introduced Fault	Figure	Symptom
Kitchen Blender	Philips Daily HR2100/90 Blender	Plastic pin that actuates the safety switch broken.	2a	Unresponsiveness
Radio CD player	Philips AZ700T	Discharged batteries	none	Unresponsiveness
		Disconnected cable plug from the speakers to PCB. Signs of burns were introduced to look like a short circuit	2b	No sound
Coffee Machine	Philips Senseo Quadrante HD7865/60	Unplugged water level sensor cable from PCB	2c	Error signal: blinking light
Vacuum Cleaner	Samsung VC07M3130V1/EN	Clogged motor fan	2d	Low suction, loud noise during operation

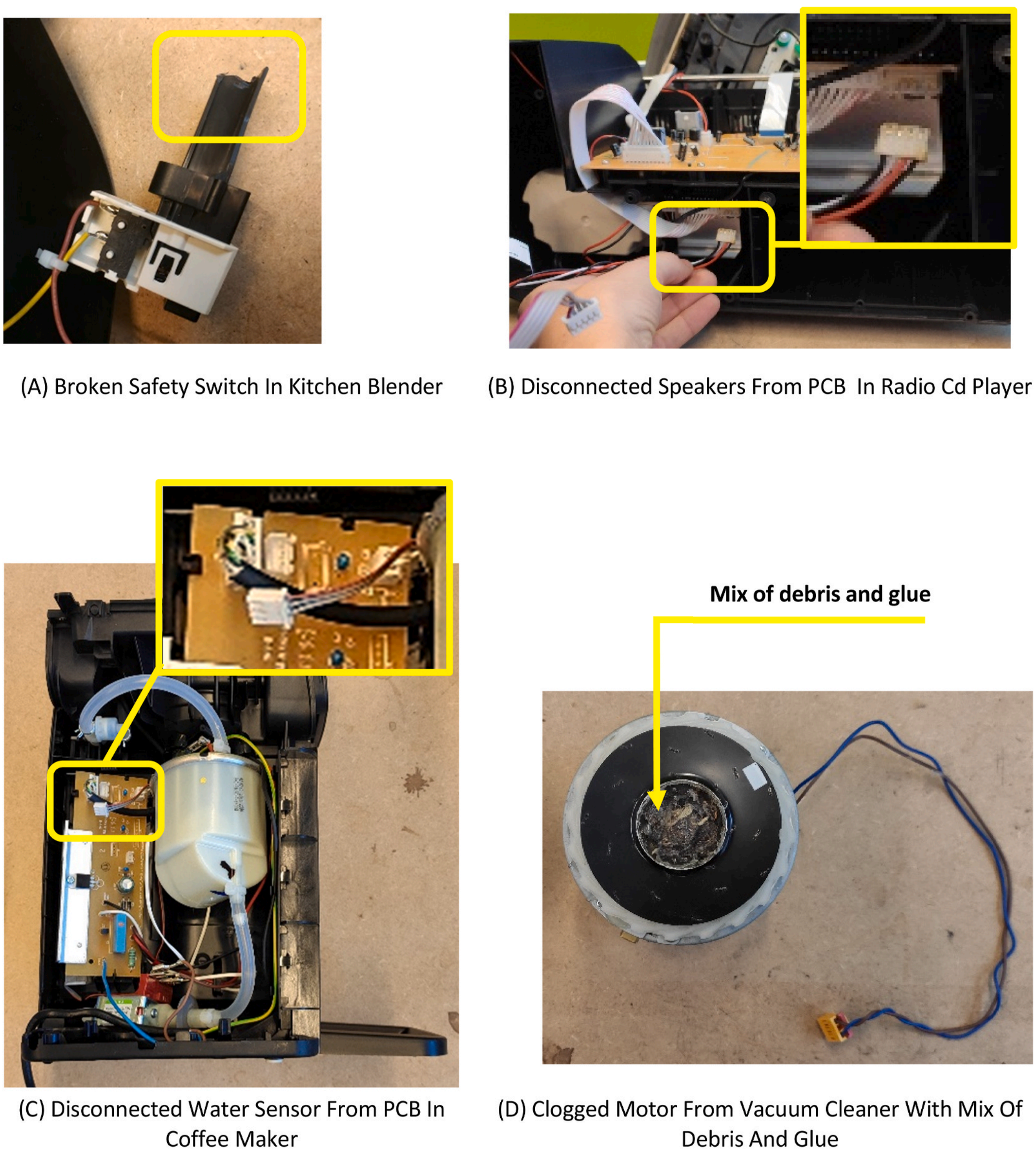

Fig. 2. Introduced faults in the products.

vacuum cleaner. We then described the think aloud method (Van Someren et al., 1994), and how they should use it. We made sure they understood the method and how to use the product by asking the participants to perform the demonstrated task themselves thinking aloud. They were given 2 min to further familiarise themselves with the product. This was then swapped with a malfunctioning one and again, we asked the participants to perform the demonstrated task while thinking aloud. We made them aware that there could be something wrong in the product, and asked them to tell us what it was.

Two researchers observed the participants. One was in charge of facilitating the sessions; the other stayed in the control room and ensured correct video recording. The facilitator only intervened if participants stopped thinking aloud or showed no progress for more than 3 min. In the first case, the facilitator would remind them and prompt

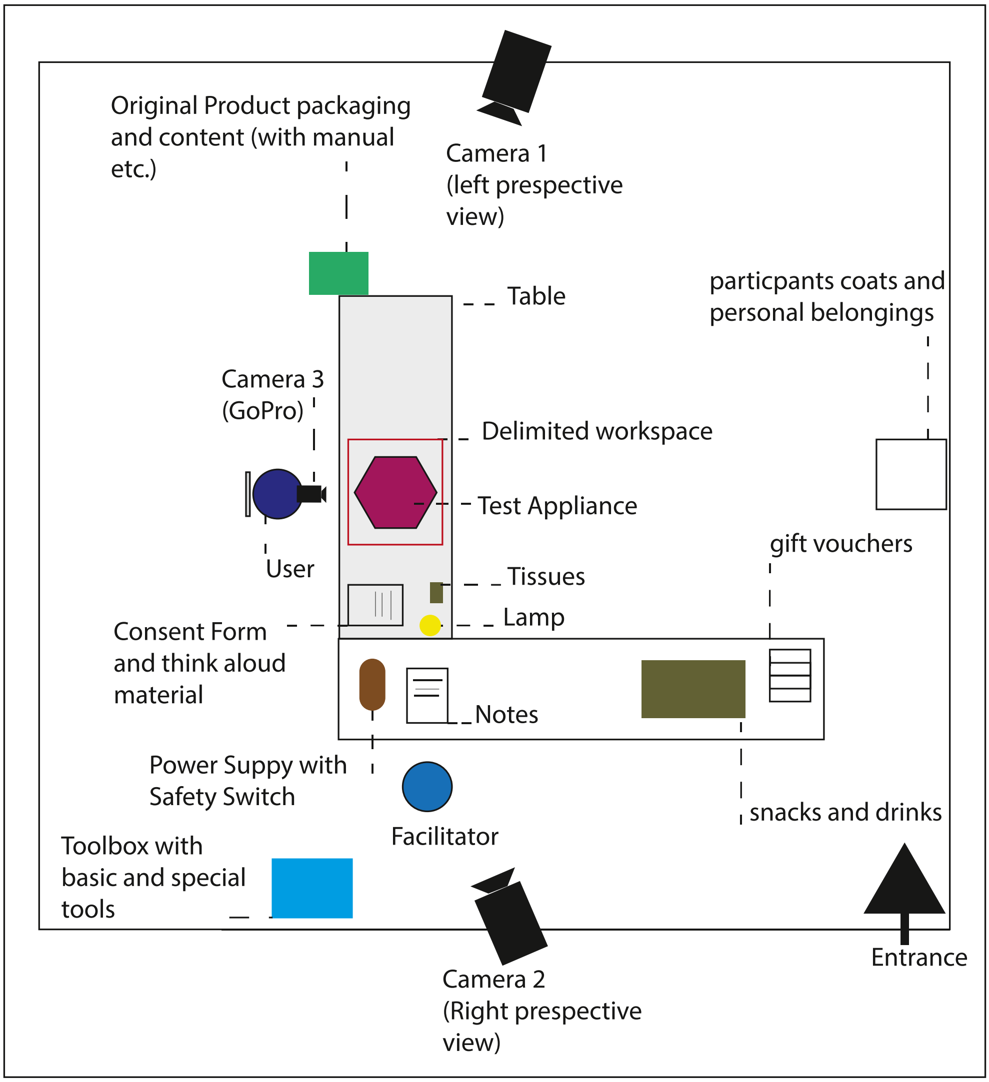

Fig. 3. Room set-up for participant observation.

them on their thoughts or motivation underlying a certain action. In the second case, if the user showed either no progress or the intention to give up, the facilitator prompted them on the issue and offered a hint to help them continue the diagnosis. The hint suggested the next action step to be taken in the disassembly process. Essentially, in a household environment, they would not be able to go further without this help and would likely stop; this was later noted as a clear barrier.

After the fault was identified or the time limit was reached, a short interview was conducted to further understand the diagnosis process and the difficulties they faced (Table 2).

We slightly modified the questions for participants who had not found the fault. For instance, instead of "how difficult was it to find the fault?" we would say, "what features made it difficult to find the fault?"

Table 2
Interview questions.

Topic	Question
Behaviour at home	What would you normally do at home if this occurred to you?
Diagnosis difficulty	How difficult, on a scale of 1–10, was it to find the fault? 1 = easy, 10 = difficult; could you explain why?
Design features	What helped you find what was wrong with the product? What made it difficult for you? How would you improve the product to make it easier for you?

After the interview, the session ended.

3.5. Data analysis

The purpose of the analysis was to understand the influence of the product's design and the users' self-reported repair experience on the diagnosis process. Therefore, we analysed the data qualitatively and quantitatively.

For the qualitative analysis, we created a case record for each participant (see example in Fig. 4). Using Adobe Illustrator software, the participants' verbatim speech, their actions, and product disassembly steps were transcribed from the videos in chronological order (see Fig. 4 – column 1). We used De Fazio's et al. (2021) disassembly map method for noting the disassembly steps. Then, we analysed the transcribed content (Fig. 4 – columns 2 and 3).

The diagnosis process and search strategies were analysed first; design features were analysed later. We used indexing to trace the fault diagnosis process. Indexing (or coding) is "a qualitative data analysis method where the researcher applies meaning to raw data by assigning key words" which "then act as signposts to themes within the data" (Bloor and Wood, 2006),. We related the verbatim transcription, observed actions, and disassembly steps presented in the case record to each of the three diagnosis steps: fault detection, location, and isolation (see Table 3). We added quotes and codes to capture the participants'

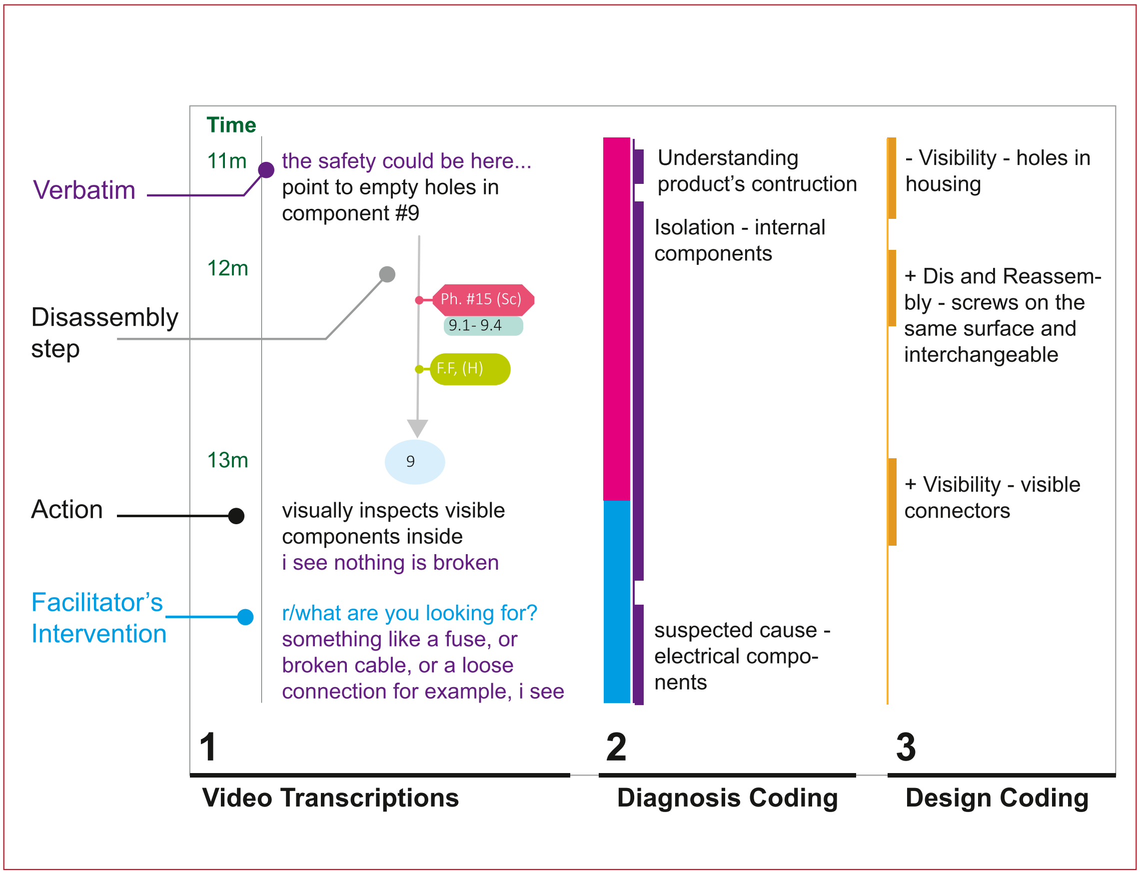

Fig. 4. Example of Case Record with labelled entries. The left column shows the transcription of the participants' thinking aloud, the observed actions, disassembly steps, and facilitator interventions in chronological order. The middle column shows the search strategies (blue bar represents a systematic strategy) and diagnosis steps and tasks related to the transcription. The right column shows coding of design principles, features, their influence (+or -), and purpose. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

expressions of frustration and facilitator interventions during the diagnosis. These codes were developed from the insights obtained during the observations.

To code the participants' search strategies, we analysed their verbalized search process and their actions. Based on the data, we could identify one strong search strategy and two types of weak strategies; which we defined using literature (see section 2.2) and our observations (see Table 3). We labelled the strong strategy as 'pinpointed', and the weak strategies as a 'systematic' and 'unstructured'.

In a second analysis step, we set out to identify the products' design features that facilitated or hindered fault diagnosis and created a list of associated design features (for instance: 'deeply recessed fasteners', 'hidden snap fits', 'long cables', etc.) by looking at instances where participants either successfully completed their diagnosis process, or wanted to give up on it. We also looked at instances where participants changed their search strategies (i.e. going from systematic to pinpointed, or from pinpointed to unstructured) to understand the design feature that might have caused this change in search strategy. See Table 7 for a full overview.

Next, we clustered the design features under a set of design principles as described in Table 4. For example, the design features 'ergonomic geometry' is clustered under 'accessibility'. These design principles were based on the literature review of design principles relevant for product repairs as presented by Den Hollander (2018). We also considered design features affecting the diagnosis process from our previous study (Pozo Arcos et al., 2020). This provided an initial set of design principles relevant for fault diagnosis, which was later used for the analysis: interchangeability of components, modularity of subassemblies, accessibility to the product's interior, visibility of the internal parts, and the feedback and information provided from the product to the user. Table 4 provides definitions for each of these design principles. Based on our data, we identified and defined two new design principles: "enable testing" and "robustness". In Table 7, we list all design principles and related design features, with short descriptions of how these facilitate or hinder fault diagnosis.

All data were coded and analysed by two researchers to minimise the risk of bias. Following recommendations for teamwork qualitative research by Milford et al. (2017), both researchers coded the case reports and checked for intercoder agreement. The reports with discrepancies in the coding were discussed and co-analysed until both researchers agreed.

Once all data had been coded and qualitatively analysed, we performed a statistical analysis to understand the influence of repair experience and design features on the diagnosis process. We tested the average time each participant spent on each strategy against the repair experience and the product type.

Time spent on each strategy was measured in minutes. We considered the time on each of the three strategies as a percentage of the total time of the experiment. The sample size was small and data was not normally distributed. Therefore, non-parametrical tests were conducted (Field, 2005). We conducted one-tailed Man-Whitney U tests ($N = 12$) to test the difference in time spent on each strategy between the two groups of participants: with repair experience vs without repair experience. We also conducted Kruskal Wallis one way analysis of variance three times to test the difference in strategies followed for the four different products ($N = 6$). This test is an extension of the Man-Whitney *U* test when more than two independent samples (products) are compared (Field, 2005).

Table 3
Coding scheme for the analysis of the diagnosis process.

Category	Definition	Code	Subcode	Example of Quotes/Action
Diagnosis Steps		*Diagnosis Tasks*		
Fault Detection	User detects the faults in the product by sensory observations	Visual	–	"[the blade] doesn't rotate''
		Designed Signal	–	" there's a blinking light"
		Auditory	–	" the sound is different"
		Tactile	–	"is very slow, there is almost no air going through"
Fault Location	User determines possible causes of failure	Suspected Cause	General Cause	"somewhere is blocking '
			Specific Component	"there's a bag .. and its full … "
			Unknown	"I don't know "
		Understanding working mechanism	–	"the air is coming in here, and its coming out this way"
Fault Isolation	user checks the condition of the components	Understanding a product's construction	–	"behind here there must be the motor" "I need three screws to get it (the motor) out"
		Isolation	[Action]	Example of actions: check blockage, clean, use subassembly without X
		Successful diagnosis of	[Component]	'"this is not the problem, and this is not the problem" "this looks ok"
Process interruptions				
Interruption during diagnosis	The diagnosis process is interrupted by the participant or the facilitator	User	Giving up	"If I did it at home, I would put it back together again" "I think I would throw it away at this moment"
			Expressing doubts/confusion	''strange'' ''I don't know what to do … "
			Unable to access the interior	"I can't get it open"
			Expressing difficulties	"This isn't so easy" "It's more difficult than I thought"
		Facilitator intervention	–	(instances where the facilitator intervened)
Search Strategies				
Pinpointed Strategy	The participant knows how to go about solving the problem. User has a correct suspicion of possible component at fault and directly searches those	Based on codes: "suspected cause" and "[action]"	–	
Systematic strategy	The participant does not know what to do directly to solve the problem. User has a general suspected cause of failure e.g. Blockage and follows an ordered and structured search in the product	Based on codes: "suspected cause" and "[action]"	–	
Unstructured strategy	Checking all potential solution candidates in no particular order. No clear suspected cause of failure and follows an unordered search in the product.	Based on codes: "suspected cause" and "[action]"	–	

4. Results

In this section, we present the results of the qualitative and statistical analysis of the user observations. Section 4.1 describes the diagnosis process and the strategies followed to diagnose the products; Section 4.2 presents factors relevant to the diagnosis process; and Section 4.3 presents a summary of the results.

4.1. Diagnosis process and strategies

The diagnosis process started with fault detection. All participants were able to detect the symptoms in the product (e.g. "not working", "low suction" etc.). However, in some cases, not all users noticed the same symptom. For instance, in the coffee maker, three participants noticed the error code and directly related it to a problem with the water level, whereas the other three just noted unresponsiveness and did not see the error code. The participants who detected the error code had used a product with a similar error code in the past.

Fault detection triggered the search strategy; participants performed iterative fault location and isolation tasks on the suspected components until the fault was found. During fault location, the participants interacted with the product to make an, not necessarily correct, educated guess about possible causes of malfunction and to understand how the product was built in order to reach the suspected components during fault isolation.

Fault isolation consisted of checking the condition of the "possible causes". This required accessing the components, often by first disassembling the product. We observed two ways of inspecting components: (a) directly, by checking the suspected component; or (b) indirectly, by checking the system without the suspected component, for instance, by running the vacuum cleaner without the hose to check the suction power if a clogged hose was suspected. The diagnosis process was restarted if functional testing revealed that the product continued to malfunction.

A summary of the user observations is presented in Fig. 5, visualising the search strategies followed by the participants and key observations such as diagnosis steps, instances of the user willing to give up, and facilitator interventions.

We distinguish between initial search strategies, adopted directly after noticing the symptom; and subsequent search strategies followed after obtaining feedback from the initial strategy. Table 5 presents a quantitative summary of the initial strategies. The results show that noticing the radio's unresponsiveness, the coffeemaker's error code, and the vacuum cleaner's sound signal led to pinpointed initial strategy. The participants directly related the symptoms to a possible fault without further interacting with the product, which indicates that easily recognisable signals such as light or sounds and/or previous experience with similar products facilitate symptom-to-cause associations.

Initial pinpointed strategies only resulted in a successful diagnosis in the case of the radio for the fault caused by the discharged batteries, which indicates that the initial suspected cause was plausible and correct. Changes from an initial pinpointed to less directed strategies (Fig. 5) occurred after all the initially suspected components were diagnosed, but not defective. In these instances, design cues were absent or participants were unable to follow them properly, causing them to change to a less directed strategy.

Changes towards directed strategies (showed in Fig. 5) occurred when the participants were able to follow different design cues. Participants went from systematic to pinpointed once they had located the fault. In the case of the radio, we could clearly relate the change from systematic to pinpointed to the text display that communicated the process being executed in the product such as reading CD and playing audio. All the participants that interacted with this feature followed the same search strategy, which indicates that design can offer diagnosis guidance by directing the participants towards more directed strategies. However, while five of the six participants were able to locate the fault without disassembly and attempted to isolate the fault, the subsequent difficulty of the disassembly made it impossible for them to achieve a

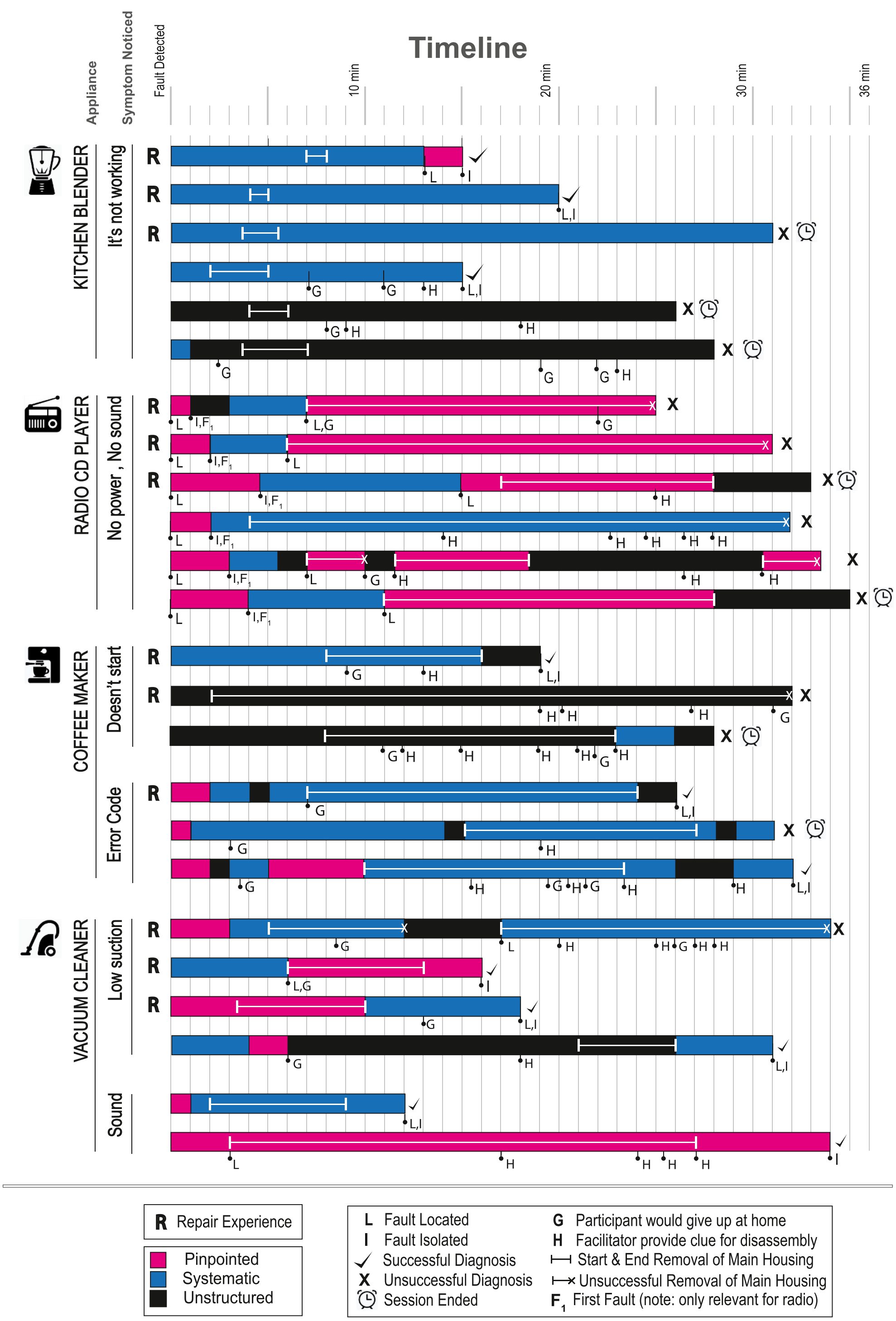

Fig. 5. Summary of 24 User Observations grouped by product type and symptom detected by the participants.

successful diagnosis. None of the participants could isolate the fault despite having located it. Therefore, it seems that if participants are able to locate the fault without disassembly, they are more likely to continue the diagnosis; and that product disassembly hinders a successful diagnosis.

Fig. 5 also shows moments when the participants would have given up the diagnosis if in a real-life situation. The majority of these moments were noted for the group of participants "without repair experience" (8/12). The most frequently expressed reason was being afraid of worsening the product or breaking it due to the difficulty of disassembly. Consequently, during the interview, 7 of the 12 non-experienced participants stated preferring to give it to someone with more repair experience (friends/family with expertise in repairing products, or repair cafes and professionals). Furthermore, the lowest number of participants who would give up was observed for the radio.

Of the 24 participants, 17 were able to locate the faults, but only 11 could successfully diagnose the product (that is isolate the fault). In 6 of 13 instances, the diagnosis failed because the participants could not remove the outer casing, hence, they could not progress with the diagnosis. Other unsuccessful instances (7/13) occurred because the session ended while the participants were following unstructured strategies (5/7). Therefore, the lack of design guidance and the need to disassemble the product hindered the steps of location and isolation.

Table 4
Design Principles relevant for Fault Diagnosis.

Design Principle	Definition used in this study
Interchangeability	"Controlling dimensional and functional tolerances of manufactured parts and assemblies to assure that [a part that is expected to fail or has failed] soon can be replaced in the field with no physical rework required for achieving a physical fit, and with a minimum of adjustments needed for achieving proper functioning" (Moss, 1985, p.37)
Modularity	Enforcing "conformance of assembly configurations to dimensional standards based on modular 'building block' units of standardised size, shape, and interface locations (e.g., locations for mating attachment or mounting points and input/output line connectors), in order to simplify maintenance tasks by enabling the use of standardised assembly/disassembly procedures" (Moss, 1985, p. 36, p. 36)
Accessibility	Features and spatial arrangements in the product or parts that provide access to components without the complete removal of a part (Moss, 1985)
Visibility	Features related to the visible surfaces of a component or its visual inspection (Pozo Arcos et al., 2020)
Feedback To User and information to user	Designed signals in the form of text, light, sound or movement provided by the product in response to an interaction and information provided to the user not embodied in the main assembly e.g. Manual, stickers (Pozo Arcos et al., 2020)
Dis And Reassembly	Facilitating the process of removal of parts from and/or placement of parts in a product "while ensuring that there is no impairment of the parts [or product] due to the process (Brennan et al., 1994, p. 59)
Redundancy	Providing an excess of functionality and/or material in products or parts, for example to allow for normal wear or removal of material as part of a recovery intervention (Keoleian and Menery, 1993) or to prevent interruptions in the functioning of a product (Kuo et al., 2001)
Enable Testing	Features that allow testing the condition of the components or subassemblies
Robustness	Features that allow the user to perform rough actions to inspect the component without disturbing its condition

4.2. Influential factors for the diagnosis process

4.2.1. (Self-reported) repair experience

Table 6 shows that the group with self-reported repair experience used more structured strategies; they had higher averages for pinpointed and systematic. In contrast, the group without repair experience scored higher for unstructured strategy. These differences are not significant, so can only be regarded as being indicative.

We also analysed whether the participants' self-reported repair experience influenced the required time for disassembly; however, we did not run a statistical test because some participants required clues from the facilitator, which would invalidate the analysis. Almost all the participants "without repair experience" (10/12) required help during the disassembly process compared to 3/12 from the group "with repair experience" (see Fig. 5). This indicates that self-reported repair experience does influence the disassembly process.

4.2.2. Product type

We observed major differences in the required time for the disassembly and the chosen search strategy between the products. The kitchen blender took the least time to disassemble (2 min), followed by the vacuum cleaner (12 min), the coffee maker (17 min), and the radio CD player (18min). Regarding the search strategies, the results showed a significant difference in the use of the pinpointed strategy ($p = 0.010$), with the highest use for the radio and the vacuum cleaner (Fig. 6). Both products showed the least use of unstructured strategies. Our results indicate that enabling and hampering design features strongly affects the choice of specific strategies.

Qualitative analysis revealed how design features affected the different search strategies and the feasibility of the diagnosis tasks (see Table 7). In the following sections, we discuss the relationship between design features and the success of search strategies.

In a pinpointed strategy, the features providing "feedback to user" were most useful for a correct symptom-to-cause deduction, which led to a correct location of the fault. The combined principles of component accessibility and visibility were most useful during fault isolation when the participants inspected specific components. However, accessibility alone does not seem to be sufficient. For the kitchen blender, we observed that the broken safety pin was accessible but not easily visible. The colour of the pin and the housing were the same which resulted in the blender being disassembled to the pin by 4/6 users instead of simply accessing the pin from the outside. Pinpointed strategies were unsuccessful in cases where the participants relied on their own heuristic knowledge in the absence of guidance by the product.

In a systematic strategy, participants identified possible causes of failure by learning how the components were assembled and worked together. In successful systematic search strategies, location and isolation occurred simultaneously (see Fig. 5). The visibility of components in the product offered guidance during fault location. However, when the components were visible but assembled at different disassembly levels (same level components can be disassembled in parallel), the participants had difficulties understanding how the product was constructed, resulting in a delay in locating the fault and unsuccessful diagnosis. Both strategies show that component accessibility and visibility are key to facilitating fault location.

Unstructured strategies resulted in a successful diagnosis for the coffee maker once all components were visible at the same disassembly level, i.e. a full view of component location and isolation facilitate an unstructured strategy.

4.3. Summary of results

All participants started the diagnosis process and attempted to identify the faults. Their search strategies were significantly influenced by the product's design and not significantly influenced by the participants' self-declared repair experience. Almost half (46%) of the

Table 5
Overview of Detected Symptoms and Initial Search Strategies per product.

Product	Observed Symptoms	Participants	Initial Strategy		
			Pinpointed	Systematic	Unstructured
Blender	Unresponsiveness	6	0	5	1
Radio	Fault 1: unresponsiveness	6	6	0	0
	Fault 2: underperformance	6	0	6	0
Coffee	underperformance	3	0	1	2
	Error code	3	3	0	0
Vacuum Cleaner	underperformance	4	2	2	0
	Sound Signal	2	2	0	0

Note. Results in bold text highlight instances in which all the participants of the observational study followed the same initial strategy.

Table 6
–Statistical analysis on search strategies for both participant groups.

Strategy	Time Spent on Strategy		P Value Mann-Whitney *U* Test*
	with repair experience	without repair experience	
Pinpointed	32%	20%	0.26
Systematic	54%	44%	0.22
Unstructured	14%	36%	0.15

*(significance at $P < 0.05$).

participants could successfully diagnose the products within the given timeframe (40 min). Design features that most hindered the fault diagnosis process were the difficulty of the product's disassembly (in particular for the non-experienced group) and the lack of guidance provided by the product, which resulted in the pursuing of unstructured search strategies and, as a consequence, insufficient time to finish the diagnosis.

5. Discussion

We set out to understand the effects of self-reported repair skills and the product's design on the process of fault diagnosis. In this section, we discuss our findings and provide an initial set of design guidelines to facilitate fault diagnosis for end-users.

5.1. About the process of fault diagnosis

Our results reflect the framework of the process of fault diagnosis presented in section 2.1: participants go through the diagnosis steps of fault detection, location, and isolation. However, we also observed that participants iterated between the stages of fault location and isolation instead of following a linear sequence as suggested by the framework. Consequently, a framework incorporating this new insight is presented in Fig. 7. This framework indicates that, for an effective diagnosis, symptom-to-cause deduction should be facilitated so that the number of iterations between location and isolation is minimal.

5.2. About influential factors for fault diagnosis

Our findings show that repair experience and product-specific knowledge (provided by previous experience using similar products) can facilitate the diagnosis process, but that design features are more influential for successful diagnosis. We observed that the product's design determines the feasibility of the diagnosis tasks and offers guidance during the diagnosis, and thus influences the user's decision to proceed with the diagnosis. Self-reported repair experience appears helpful for the disassembly process but not decisive for structured search strategies, hence it does not influence the symptom-to-cause deduction process. Furthermore, product-specific knowledge facilitates the recognition of designed signals but does not guarantee successful diagnosis.

The difficulty of product disassembly, especially removing the outer housing of the product, often hindered the diagnosis process. It was the most common cause of frustration among participants, frequently provoking the reaction of giving up, and was a major cause of unsuccessful diagnosis. Difficulty of product disassembly is reported as one of the barriers for repair (Bovea et al., 2016; Flipsen et al., 2017; Pérez-Belis et al., 2017). Our study adds to this literature by indicating that difficulty of disassembly is also a barrier for successful fault diagnosis.

In addition, difficulty of product disassembly particularly affected the group "without repair experience". They required more clues for disassembly and were more likely to give up the diagnosis. Thus, self-reported repair experience appears to play a role in overcoming the difficulty of the disassembly. This result coincides with the findings of Mourris and Rouse (1985) who concluded that a successful troubleshooter should have the skill of knowing how to repair or replace a component.

Although the study revealed that using product-specific knowledge during diagnosis resulted in more directed search strategies, these were not always successful as they were based on product-specific knowledge from previous experiences and not on the product being diagnosed. Therefore, while our findings recognise the benefits of end user product-specific knowledge, for optimal fault diagnosis and repair by all end users, the diagnosis should be more reliant on the product's design.

5.3. Initial design guidelines to facilitate fault diagnosis

Some products gave participants more information and guidance when detecting and locating faults, resulting in more structured search strategies. Moreover, we observed that in the absence of guidance features, the participants relied on component visibility and accessibility to discover how the product was built and how the different components worked together. As a result, they could deduce possible causes of failure and corrective actions, i.e., if components could be seen and accessed, successful diagnosis was achievable. Furthermore, faults in components were easier to isolate when disassembly was minimal and easy to perform, e.g. no tools required, and the components were functionally independent. These observations led us to develop a set of design guidelines that facilitate fault diagnosis. These are based on the design principles and design features of Table 7.

The design guidelines are listed in Table 8. They encapsulate multiple design principles relevant for an easy diagnosis. In the context of this study, "design guidelines" are defined as practical recommendations on how to apply design principles for fault diagnosis. "Design principles" are defined as general directions of improvement; e.g., increasing accessibility generally improves diagnosis, as does increasing modularity and visibility. Designers can use these guidelines to create easy-to-diagnose products. The guidelines we present here are a first step towards a complete set of design guidelines for fault diagnosis; additional research, iteration, and validation are needed for the guidelines to fully mature.

These preliminary guidelines show similarities with previous guidelines on design for repair. Guidelines 2 and 5 aim to ease product disassembly to the component level. Ease of disassembly is a well-

Table 7
Design Principles and Features Facilitating (+) or Hampering (−) the Diagnosis Process and its Relevance at Each Diagnosis Stage: Detection (D), Location (L), and Isolation (I).

DESIGN PRINCIPLES, Design Features		Relevance for the Diagnosis Process			
ACCESSIBILITY	Ergonomic geometry of access points to components Sectionable component Long cables Lid Opening in the casing		+L	+I	Quick inspection of components without removal of fasteners or components.
	Non-ergonomic geometry			-I	Difficult inspection of components, could imply further disassembly
	Non removable encapsulation			-I	Components cannot be checked
DISASSEMBLY	Seams (of housing) Visible fastener head			+I	Understand product's construction
	Easy-to-detach (Detachment within 2 actions, low force and without any tools)			+I	Component release
	Many (5+) screws on different surfaces for a single component (housing) Hidden high force snap fits* Screws located away from component they fasten Deeply recessed fasteners			-I	Understand product's construction + Component Release * and provokes fear of breaking the product when attempting to detach
	Non removable encapsulation			-I	Components cannot be disassembled
INTERCHANGEABILITY	Easily replaceable standard components			+I	Able to quickly isolate the faulty component by replacing with a working one (If spare parts are readily available)
MODULARITY	The device is built from individually distinct functional units		+L	+I	Allows condition inspection of individually distinct functional units (in particular, when these can operate independently)
REDUNDANCY	More than one way of delivering a function	+D	+L	+I	Certainty for fault location
ROBUSTNESS	Materials and construction are unlikely to fail, even if the product is treated roughly			+I	Allows inspection and disassembly without fear of damaging the device or components
TESTING	Non-isolated electrical measuring points			+I	Facilitate the measurements with multimeter
USER FEEDBACK & INFORMATION	Light when powered Click sound during attachment/ detachment	+D	+L	+I	Confirms the user that components are working
	Error Signal in the form of Blinking lights	+D	+L		Directs repair to potentially defective components, however, the study shows that interpreting their meaning required previous experience with using similar products.
	Display with text	+D	+L		Communicates the process being performed or executed
	Colour contrasting with grime			+I	Quickly check the condition (cleanness) of component
	Engraved labels and marking in the product	+D		+I	Guidance on correct usage of product
VISIBILITY	Material transparency Full view of components*	+D	+L	+I	Quick Inspection without disassembly * and understand working mechanism of the product
	Coloured wires Visible relationship between components		+L		Understand working mechanism of the product
	Symmetric positioning of components			+I	Inspection by comparison
	Non-contrasting colour between components		-L	-I	Identify different components
	Components of same functional subsystems at different disassembly levels (>2 level)		-L		Understand working mechanism of the product

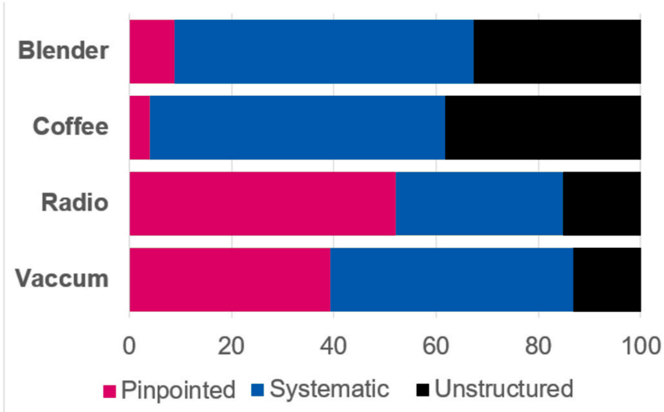

Fig. 6. Ratio of followed search strategies per product type.

recognized design principle for circular products. It is usually valued for facilitating replacement of broken components (Blomsma et al., 2019; Bovea and Pérez-Belis, 2018; Shahbazi and Jönbrink, 2020). Also, visibility of components, needed to guide users through the disassembly (guideline 2) has been identified as a relevant criterion for product reparability (Flipsen et al., 2019).

However, our guidelines provide new directions to ease the diagnosis, and consequently, the repair of products for end users. First, they include design principles that were not related to diagnosis and repair before, e.g. the principles of robustness and enabling testing (den Hollander, 2018; Pozo Arcos et al., 2020). Second, guideline 3 expands guidelines for inspection from Go et al. (2015). It provides additional means to ease fault isolation. Third, guideline 1 aims to facilitate fault detection and fault location. Such a recommendation had not been recognized in literature on design for repair before. Fourth and last, guideline 4 puts forward the idea of avoiding the need to disassemble the product and instead facilitate means to know the condition of components from outside.

These guidelines are a valuable addition to the currently available ‘design for repair’ guidelines. They show how design for fault diagnosis stresses the importance of providing relevant and easy-to-access feedback to end-users about the state of the product and its components. Where design for repair guidelines tend to focus on product architecture and disassembly, the design for fault diagnosis guidelines presented here focus on the end-user’s ability to ‘read’ the condition of the product, preferably without the need for disassembly.

5.4. *Limitations and recommendations for further study*

Due to the response and availability, we mainly recruited participants aged 45–65. Therefore, the data may not be fully representative of the general population. A different age group might have had different experiences using the product and repairing it. Furthermore, we note that our experiment may not be a fully accurate representation of a real-life scenario, as some participants stated that they would not have repaired the product if at home. However, as our primary aim was to investigate how design features and experience affect search strategies, this is not considered to limit the validity of the results. Finally, we only included four products, which limited the number of analysed design features and faults. Extending the range of products is likely to bring forward additional relevant design features.

We recommend that future studies use a greater range of products and that they analyse the impact of design guidelines on design and repair practice. Research questions could include:

- What would be the impact on diagnosis and repairs if products were designed following our set of initial guidelines?
- How could designers use these initial design guidelines and how could these be implemented into practice?

6. Conclusion

We investigated the effects of repair skills and the product’s design on the fault diagnosis of consumer products by end-users. The diagnosis process was studied qualitatively and quantitatively through an observational study with 24 participants who were asked to repair four defective consumer products in a controlled setting while thinking aloud.

Analysis of the findings resulted in a detailed description of the end user fault diagnosis process. The product’s design had a major influence on the effectiveness of fault diagnosis, both in terms of time and search strategy. It affected the feasibility of the diagnosis tasks and the information and guidance the user could obtain from the product during the diagnosis. Product disassembly was found to be a major barrier to diagnosis, and a reason for users wanting to stop the process.

This study is one of the first to explore in detail the process of fault diagnosis of consumer products by their end-users. It gives rich insights in the way people struggle with fault diagnosis and provides evidence of the importance of the product’s design for a successful diagnosis. These insights, translated by us into a set of preliminary product design guidelines, will assist the development of better Design for Reparability methods and contribute to the body of knowledge of product

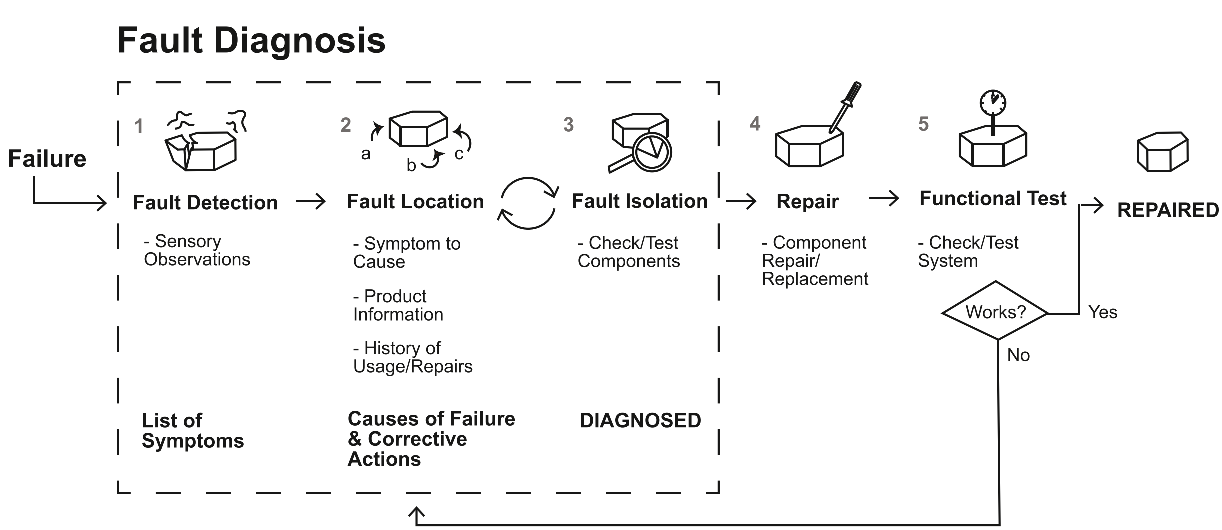

Fig. 7. Updated framework of the process of fault diagnosis by end-users.

Table 8
– Design Guidelines to Facilitate Fault Diagnosis and Design Principles to which they are associated.

Design Guidelines	Design Principles								
	Accessibility	Disassembly	Interchangeability	Modularity	Redundancy	Robustness	Testing	User Feedback & Information	Visibility
1. **Facilitate fault detection and symptom-to-cause deduction by giving timely and understandable feedback that does not require product specific knowledge.** For instance by providing sound or text signals that communicate the correct appliance usage or the process being executed in the product.					●			●	●
2. **Facilitate navigating through the product's construction.** For instance by arranging components at the same disassembly level and making their relationship visible.		●							●
3. **Facilitate the inspection of product components.** For instance by making components functionally distinct, providing them with testing ports or including features that inherently communicate their condition.	●	●	●	●	●	●	●	●	●
4. **Minimise the need to disassemble the product.** For instance by including lids or doors to access to the components, or features that facilitate knowing their condition onsite such as testing ports, transparent materials or contrasting material colours.	●						●	●	●
5. **If product disassembly is needed, facilitate it.** For instance by giving ergonomic dimensions to points of access to components, reducing the number and diversity of fasteners and making them visible.	●	●		●		●			●

reparability.

Furthermore, these results are relevant for future product reparability policy and legislation. The Circular Economy Action Plan by the European Commission aims to support the "Right to Repair"(European Commission, 2020). Accordingly, Ecodesign Regulations include reparability requirements. The process of fault diagnosis is an essential step in a repair process. Hence, the insights and guidelines provided in this study could be used to put in place measures to promote designs that ease the fault diagnosis process.

CRediT authorship contribution statement

Beatriz Pozo Arcos: Conceptualization, Investigation, Writing – original draft. **Sagar Dangal:** Investigation, Writing – review & editing. **Conny Bakker:** Conceptualization, Writing – review & editing, Supervision. **Jeremy Faludi:** Writing – review & editing, Supervision. **Ruud Balkenende:** Conceptualization, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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