International Journal on Interactive Design and Manufacturing (IJIDeM)
https://doi.org/10.1007/s12008-023-01648-3

ORIGINAL ARTICLE

The form-affordance-function (FAF) triangle of design

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Received: 30 October 2022 / Accepted: 16 November 2023

Abstract

For centuries, the relationship between form and function has been a point of debate in the communities of architecture and design, leading to the development of various theories which have attempted to establish a tangible relationship between these two entities. Besides, the concept of affordance, adopted from Gibson's ecological psychology theory, has appeared as a widely-used concept in design practice and research. Nevertheless, while it is generally accepted that these concepts have close dependencies and interactions, it appears that there is no explicit theoretical framework that relates three of the most fundamental concepts of design, namely form, function, and affordance. This paper aims to analyze the concept of affordance in the context of industrial design, where we attempt to develop insights into the role of affordances in relation to form and function. To this end, we define the form-affordance-function (FAF) triangle of design as a major contributor to the establishment of a partial product design specification (PDS) in the design process. We present several examples to investigate the position of affordances in competition with other design considerations such as engineering performance, ergonomics, and aesthetics. The insights into these relationships could have potential implications for designers in making informed early-stage design decisions.

Keywords Affordance · Form versus function · Aesthetics · Industrial design and product architecture · Form-affordance-function (FAF) triangle

1 Introduction

From the stone age to the digital age, physical products have been conceived, designed, fabricated, and evaluated considering two fundamental aspects: (1) *formal specifications*, and (2) *functional qualities*. More specifically, the relationship between *form* and *function* has been a point of debate in the communities of architecture and design, leading to the development of various theories which have attempted to establish a tangible relationship between these two entities [1].

Moreover, the concept of *affordance*, adopted from Gibson's ecological psychology theory [2], has been a widely-used concept in industrial design and product architecture [3–12]. From a broader perspective, the theory of affordances has been extended and exploited in a diverse range of fields including ecological psychology [13–15], cognitive science [16–20], neuroscience [21–30], architecture and environmental design [31–43], human–computer interaction (HCI) [44–52], marketing and management [53–67], education and pedagogy [68–72], digital work and socialization [73–101], and robotics and artificial intelligence (AI) [102–109]. A pictorial overview of the abovementioned fields is presented in Fig. 1.

While it is generally accepted that three of the most fundamental concepts of design, namely form, function, and affordance, have close dependencies and interactions, it appears that there is no explicit theoretical framework that relates them. In this paper, these three interacting concepts are represented as the *form-affordance-function* (*FAF*) triangle, illustrated in Fig. 2A.

Set in the context of industrial design and product architecture, this paper aims to explore the interactions of affordances with form and function. To this end, we critically examine the evolution of the concept of affordance, followed by attempting to develop insights into its interactions with form and function through several case studies. More specifically, we present various examples to investigate the position of affordances in competition with other design considerations such

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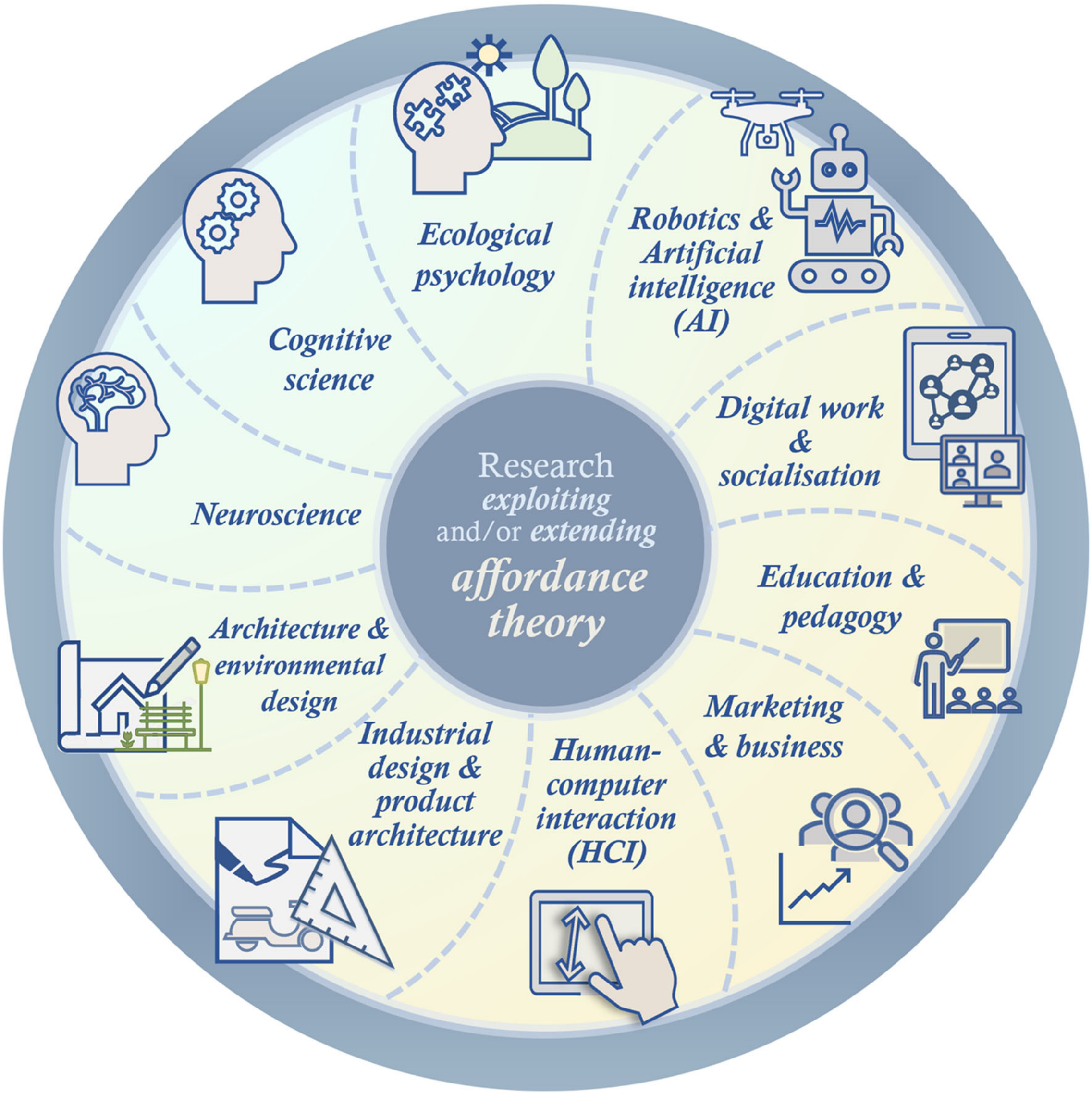

Fig. 1 A pictorial overview of various fields of research exploiting and/or extending the theory of affordances

as engineering performance, ergonomics, and aesthetics. The insights into these relationships could have potential implications for designers in making informed early-stage design decisions.

2 Affordance: concept and adoption by the design community

2.1 Gibson's theory, Norman's adoption, and subsequent confusions

For a long time, cognitive theorists believed in the assumption that human beings *sense* their environment as a "*secondary phase within the process of perception itself*" [110]. In the late 1970s, the ecological psychologist J. J. Gibson claimed that animals—in order to sense their environment—did not follow this two-phase process [110–113]. Gibson introduced the theory of *affordances* [114], where he portrayed the *environment* as the *surfaces* that separate *substances* form the living *medium* of animals. Using this ecological context, he defined the affordances of the environment to be "what it *offers* the animal, what it *provides* or *furnishes*, either for good or ill". Importantly, Gibson postulated that the affordances of any object in an environment are perceived *immediately* and *directly* [110, 114]. This notion was, in particular, a critique of the view of some cognitive psychologists who considered the brain to be an intermediary in the perception process that interprets the images transmitted via light sources to the retina [115].

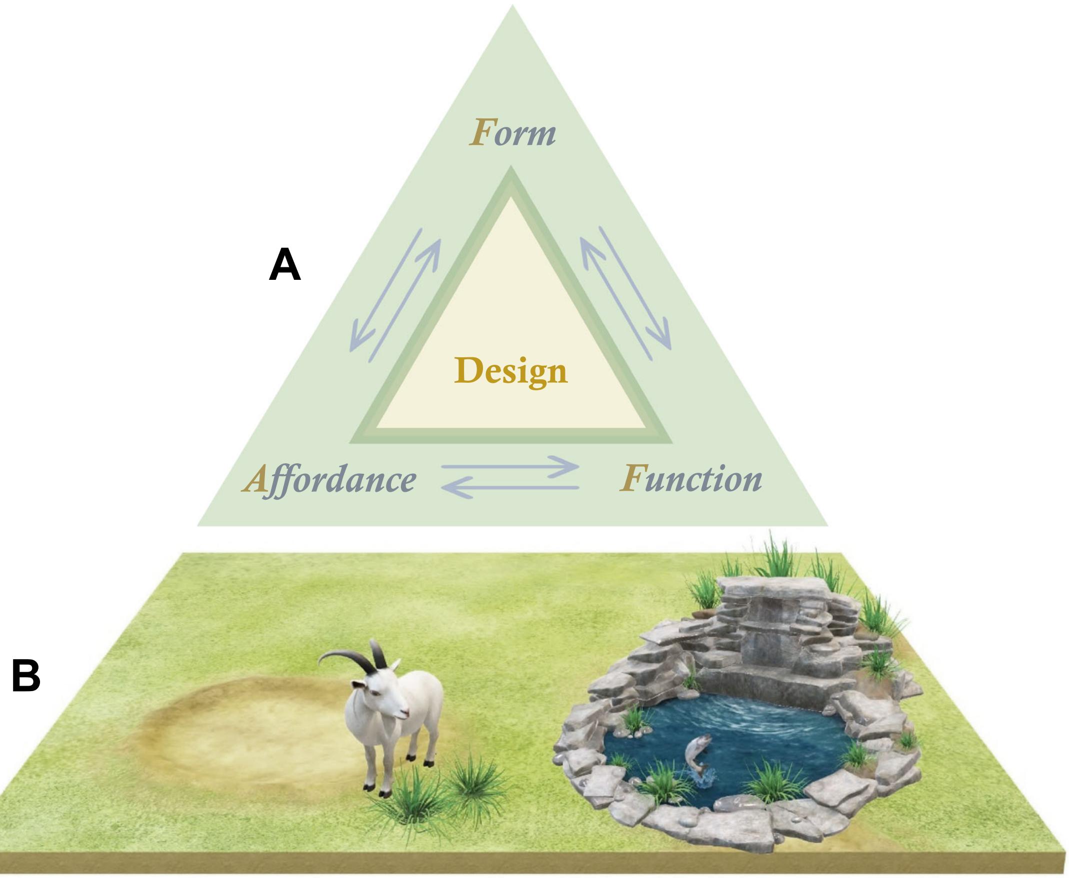

Fig. 2 **A** The collection of three interacting concepts of design represented as the form-affordance-function (FAF) triangle. **B** An example ecological context for Gibson's theory of affordances: water affords drinking for the goat which lives in the air as the medium, whilst for the fish, the water is the living medium

It is important to know that in this theory, affordance is determined relative to a given animal. For example, as depicted in Fig. 2B, the water affords drinking for the goat which lives in the air as the medium, whilst for the fish, the water is the living medium. Furthermore, for the goat, the 'terrestrial surface' and 'grass' afford 'support' and 'eating', respectively.

In the early 1990s, Turvey [116] introduced the concept of 'disposition' to Gibson's theory of affordances. In his proposed theoretical framework, "dispositional properties" (or "causal propensities") are fundamental to affordances and have three principal characteristics as follows: (1) *priority*: the disposition to take an action is prior to that action; (2) *complementarity*: dispositional properties come in pairs; and (3) *actualizability*: dispositional properties can always be actualized when conjoined with suitable circumstances. On this basis, Turvey defined an affordance as a *"particular kind of disposition, one whose complement is a dispositional property of an organism* [116]", and the complement dispositions as the "*effectivities*" of the organism [117].

Human has adapted, modified, and manipulated the surfaces and substances of the environment for their own benefit. Furthermore, (s)he has made various objects with desirable affordances for a diverse range of purposes. Norman [118] adapted the concept of affordance and introduced it to the context of design, which was particularly welcomed and adopted by the communities of graphical and industrial design [119]. From his perspective, affordance refers to the *perceived and actual properties* of an object or product, chiefly those fundamental properties which can guide the user to figure out how the object or product could be used. Therefore, affordances provide the user with *strong clues* to the operations of objects and products. Norman believes that, in contrast to *complex things*, *simple things* should not need to be accompanied by labels, pictures, or instructions, otherwise they would not be successful designs. In his view, a good design is one in which "appropriate actions are perceptible and inappropriate ones invisible" [118].

Despite its widespread popularity, Norman's notion of affordance has created considerable confusion in the design community, some of which still can be found in several studies of significant general credibility. In this regard, A. J. Wells [120] states: "Like many other profound ideas, the concept of affordance is intuitively simple, but its richness makes it hard to pin down precisely". Similarly, Norman states: "Many people find affordances difficult to understand because they are relationships, not properties. Designers deal with fixed properties, so there is a temptation to say that the property is an affordance. But that is not the only problem with the concept of affordances." For example, Saffer defines affordance as "*a property, or set of properties, that provides some indication of how to interact with an object or feature*" in the second edition of his book *Designing for interaction: creating innovative applications and devices* [121].

The abovementioned inconsistency has roots in the earlier versions of *Design of Everyday Things* acronymed as *DOET*, where Norman makes the following statement:

> There already exists the start of a psychology of materials and of things, the study of affordances of objects. When used in this sense, the term *affordance* refers to the perceived and actual properties of the thing, primarily those fundamental properties that determine just how the thing could possibly be used.
> D. A. Norman, *The design of everyday things*, 2002 [118] (p.9).

On the other hand, in the revised and expanded edition (2013) of the book, Norman states:

> The term *affordance* refers to the relationship between a physical object and a person (or for that matter, any interacting agent, whether animal or human, or even machines and robots). An affordance is a relationship between the properties of an object and the capabilities of the agent that determine just how the object could possibly be used.
> D. A. Norman, *The design of everyday things: Revised and expanded edition*, 2013 [122] (p.11).

As can be seen from these two statements, Norman initially referred to affordance as the "*properties*" of an object, whereas in the later edition he reformulated it as a "*relationship*" between an object and a person. It turned out that the design community adopted his earlier notion of affordance into their research, based on which several design theories were developed. As a significant example, Hartson's adopted and extended Norman's earlier notion of affordance, introducing five kinds of affordances which are all "*design features*", that is some *properties* of an object rather than *relationships* between the object and a person [123, 124]. Section 2.3 of this paper is devoted to the study of Hartson's extended theory of affordances.

More specifically, Norman's conception of 'perceived affordance', as introduced in the first edition of *DOET* [118], caused confusion in the design community. (This also applies to the earlier version of the book entitled *The Psychology of Everyday Things*, acronymed as *POET*, published in 1988 [125]). To address this issue, Norman exploited the concept of "*signifier*", which he had previously introduced in his book *Living with Complexity* [126]. In the preface of the revised and expanded edition of *DOET* [122], published in 2013, he stated: "…although affordances make sense for interaction with physical objects, they are confusing when dealing with virtual ones. As a result, affordances have created much confusion in the world of design. Affordances define what actions are possible. Signifiers specify how people discover those possibilities: signifiers are signs, perceptible signals of what can be done. Signifiers are of far more importance to designers than are affordances."

It should be noted that, in Norman's notion of *perceived affordance*, different users would have different affordances with an object, depending on their specific conditions and experiences. Saffer [121] also highlights the "*cultural and contextual*" nature of affordances (technically, perceived affordances), notably their dependence on the user's previous experiences and knowledge. He argues that we know we *can push* a button because we *have pushed one before*. In contrast, a pair of chopsticks provides an insufficient clue about what it is for, or how it should be used, for a person to whom it is shown for the first time [121]. These views are incompatible with Gibson's view in which perception is a direct process not based on information processing [127].

2.2 Further developments of affordances in the context of design

The adoption of the theory of affordances by the design research community facilitated a more meaningful study of user experience and human–machine interactions. Over the past three decades, a range of deficiencies and vulnerabilities of traditional function-based design methods were identified by design researchers. Warell [128] discussed that function-based design approaches are not sufficient for the design of products that require the active involvement of human users, because they merely deal with the input/output nature of the concept of function, ignoring the interaction of the product or system with users [128–130].

Based on the notion of affordances, McGrenere and Ho [131] extended Gibson's definition into a framework for design and tried to shed light on the differences between usability and usefulness. They discussed that Gibson's focus was on *direct perception* which does not require "*mediation or internal processing by an actor*". As depicted in Fig. 3, direct perception has two prerequisites as follows: (1) the existence of an affordance, and (2) the existence of information that uniquely indicates that affordance in the environment. They also clarified two aspects of affordances which were not explicitly mentioned in Gibson's theory. First, affordances could be a spectrum rather than a binary set; for example, a tool might afford doing a task but with a considerable level of difficulty. Second, affordances might come in clusters; e.g., an apple affords eating, but it also affords different stages of eating consisting of biting, chewing, and swallowing. McGrenere and Ho named these *nested affordances*.

Using the context of the theory of affordances, McGrenere and Ho [131] also highlighted the relationship between usability, which concerns the information specifying an affordance, and usefulness (or utility) which relates to the actual affordance or functionality of a product, as depicted in Fig. 3A. This led them to the conclusion that designing affordances and designing the information that specifies the affordance are two different, yet closely related, aspects of design.

To demonstrate the roles and interactions of affordances, perceptual information, and constraints in packaging design, de la Fuente [132] investigated the evolution of aerosol can design (see Fig. 3B). They described that early aerosol cans had little affordances to guide the user to operate the device appropriately, that is to target and spray at a specific area. Later designs incorporated an inclined surface along with an arrow onto the actuator signifying the correct spraying direction. To further enhance the design, Febreze® Air Effects® introduced a new design concept—inspired by a conventional gun as a metaphor—where a trigger on the front affords squeezing. Importantly, the targeting direction is effectively

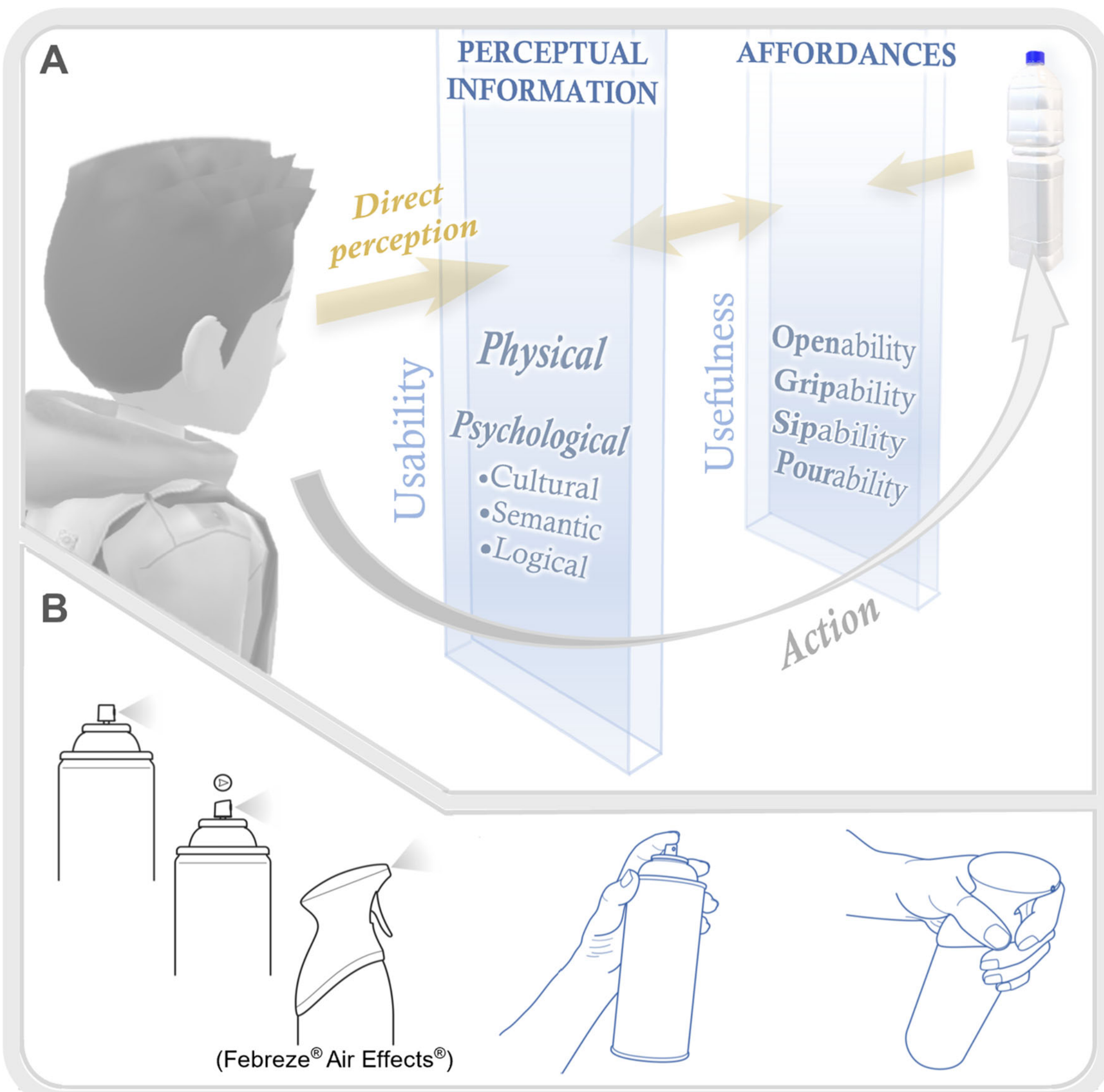

Fig. 3 **A** Usefulness and usability in the context of the theory of affordances [131] illustrated through an example of packaging design (adapted from [132]). **B** Evolution of an aerosol can design (adapted from [132] with permission)

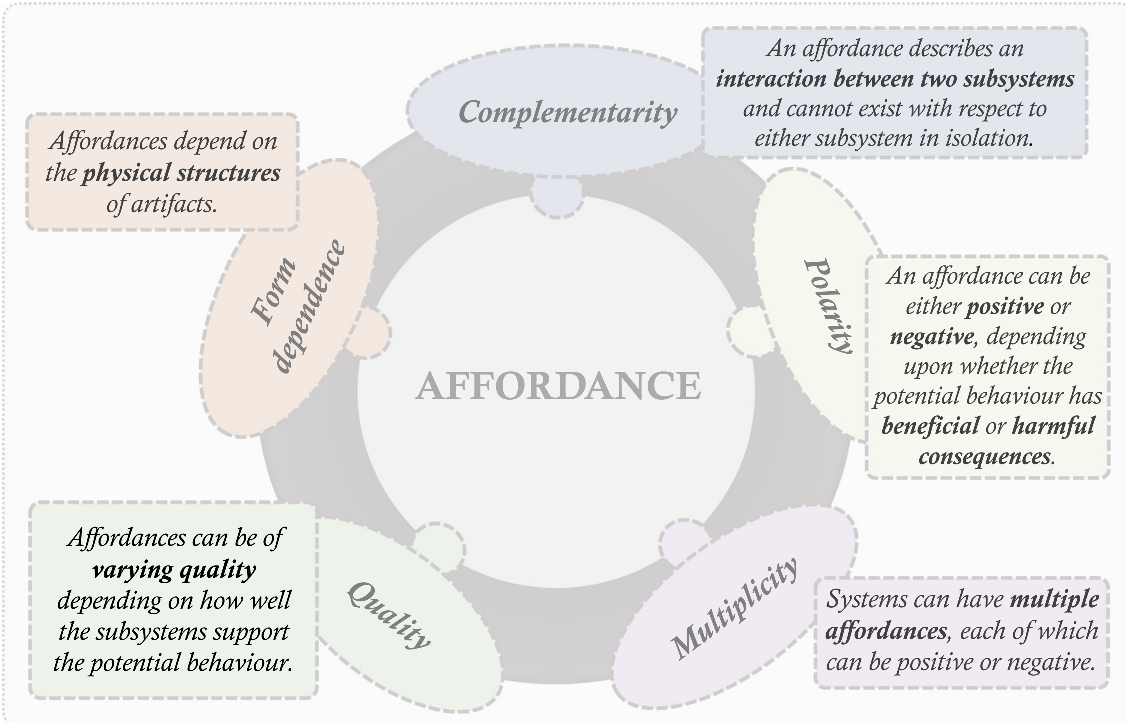

Fig. 4 General properties of an affordance (adapted from [133])

constrained by this affordance-based design, providing the user with enhanced usability [132].

Maier and Fadel [133] defined an affordance as a "*relationship between two subsystems in which a potential behavior can occur that would not be possible with either subsystem in isolation*". Generalizing the concept of affordance in the context of engineering design, they conceptualized a range of potential interactions as follows:

1. Artifact-User Affordances (AUA), which describes affordances between human users and artifacts, e.g. a heater that affords heating for the human user.
2. Artifact-Artifact Affordances (AAA), which describes affordances between two artifact subsystems, e.g. two gear elements that afford power transmission.

Drawing on Pugh's well-established concept selection matrix [134, 135] method, Maier and Fadel [133] developed an affordance-based concept selection matrix containing AUAs and AAAs. This method enables designers to compare and rank multiple concepts against multiple positive and negative affordances at an early stage of the design process (Fig. 4).

However, here we argue that the Artifact-Artifact Affordances (AAA) is a compatibility or performance index rather than an affordance, as affordances are defined in the context of perception, whereas a mechanical part (e.g. a gear) is not capable of making any perception.

2.3 Hartson's extended theory of affordances

Whilst Norman had already introduced the so-called 'perceived' and 'real' affordances drawing on Gibson's theory, Hartson extended and amplified Norman's notion of affordance in the context of user experience (UX) design. He proposed that affordances can be classified into five kinds, according to the "role they play in supporting users during interaction, reflecting user processes and the kinds of actions users make in task performance [123]", as illustrated in Fig. 5 (Hartson initially introduced the first four categories, i.e. *cognitive*, *physical*, *sensory*, and *functional* affordances, in 2003 [123]. It was followed by adding a new category, that is *emotional* affordance, in 2018 [124]).

In Hartson's terminology, Norman's 'perceived affordance' was renamed as *cognitive affordance*, which helps users with their cognitive actions, whereas Norman's 'real affordance' was called *physical affordance* (Fig. 6). He proposed their definitions as follows [124]:

1. "A ***cognitive*** affordance is a design feature that helps, aids, supports, facilitates, or enables *thinking*, *learning*, *understanding*, and *knowing* about something."

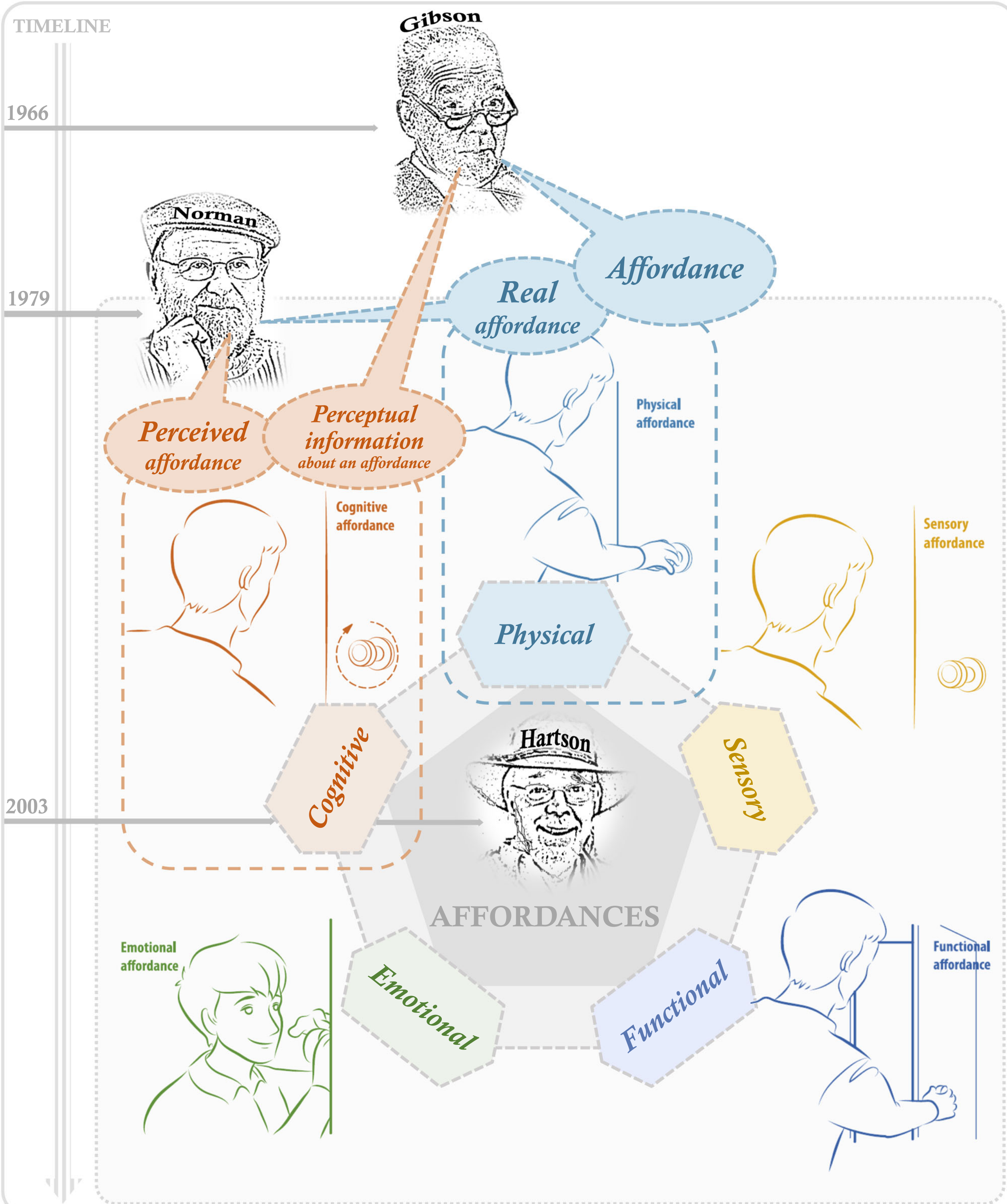

Fig. 5 Hartson's classification of five different kinds of affordances in UX design (adapted from [123, 124] with permission) and its relationship with Gibsons's and Norman's terminologies

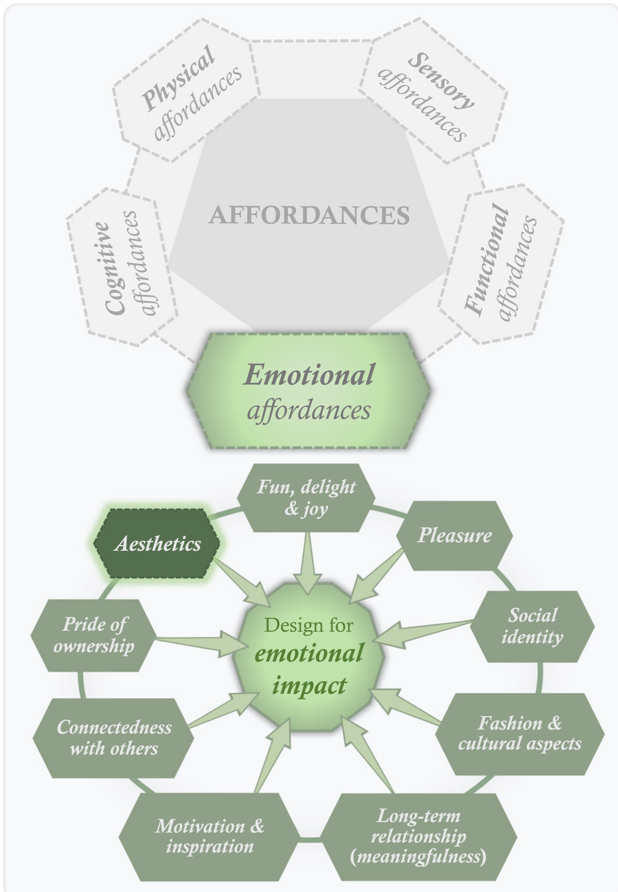

Fig. 6 Aesthetics as an emotional affordance in Hartson's model for affordances

2. "A ***physical*** affordance is a design feature that helps, aids, supports, facilitates, or enables *doing* something physically."

Hartson also introduced three new kinds of affordances with the following definitions [124]:

3. "A ***sensory*** affordance is a design feature that helps, aids, supports, facilitates, or enables users in *sensing* (e.g., seeing, hearing, feeling) something."
4. "A ***functional*** affordance is a design feature that helps users *get work done* by connecting physical user actions to the system, or backend, *functionality*."
5. "An ***emotional*** affordance is a design feature that helps a user make an *emotional connection* resulting in *emotional impact* within the user experience."

Harston presented examples for each of these kinds of affordances in the context of UX design. Importantly, Harston gives "a button label that helps users know what will happen if they click on it" as an example for (graphical) cognitive affordance, whereas Norman considers it as a 'signifier' rather than an 'affordance' [122, 124]. It also applies to textual information that is considered to be cognitive affordance by Harston, while Norman accounts them as signifiers. Figure 6 presents a visual comparison between Norman's and Hartson's notions of affordances and signifiers through two examples.

It is important to note that Harston considers aesthetics to be an *emotional need* (along with satisfaction, meaningfulness, and joy). He defines *emotional impact* as an "affective component of user experience that influences user feelings", which includes enjoyment, pleasure, fun, and satisfaction. Importantly, according to Harston's theory, *aesthetics* is an *emotional affordance* (see Fig. 7). It is in contrast to Norman's notion of affordance where affordance is a usability-related concept that might be even in conflict with aesthetics.[1]

In response to criticisms,[2] Norman wrote the book *Emotional Design* (2004) [136] which covered discussions about the role of aesthetics, pleasure, and fun in product design. Nevertheless, in that book, as well as in his following works including *Living with Complexity* (2010) [126], *The Design of Future Things* (2007) [137], and the revised and expanded edition of *DOET* (2013) [122], we cannot see any insights into the potential connections between affordances and emotional aspects such as aesthetics.

As an example, Harston lists the affordances of a Coke bottle that one thinks s/he can do with it "just by looking at it" as follows: (1) good physical affordance to grip it, (2) the functional affordance to hold liquid to drink, and (3) possibly a *nice aesthetic look* as an *emotional affordance*.

3 Affordance versus form and function: design case studies

This section presents several examples in which we deem and analyse affordances in competition with other design considerations such as engineering performance, ergonomics, and aesthetics.

[1] *"In numerous designs crucial parts are carefully hidden away. Handles on cabinets distract from some design aesthetics, and so they are deliberately made invisible or left out. The cracks that signify the existence of a door can also distract from the pure lines of the design, so these significant cues are also minimized or eliminated."* [P.100, *DOET* by D. Norman (1988)].

[2] *"When I wrote The Design of Everyday Things, my intention was not to denigrate aesthetics or emotion. I simply wanted to elevate usability to its proper place in the design world, alongside beauty and function. I thought that the topic of aesthetics was well-covered elsewhere, so I neglected it. The result has been the well-deserved criticism from designers: "If we were to follow Norman's prescription, our designs would all be usable—but they would also be ugly.""* [P.8, *Emotional Design* by D. Norman (2004)].

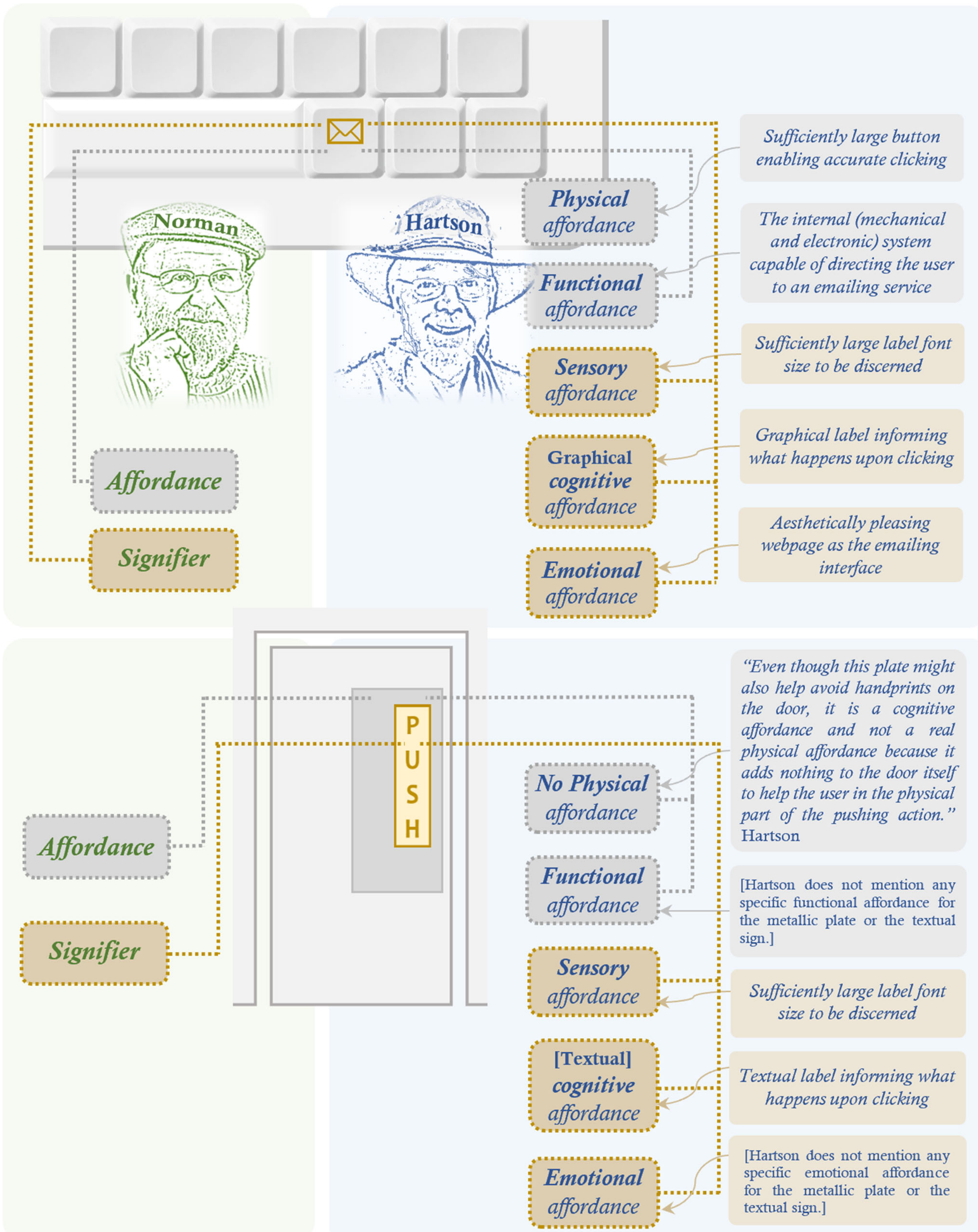

Fig. 7 A side-by-side comparative diagram for Hartson's terminology versus Norman's terminology for a mail icon on a computer keyboard (top) and a door with a metallic plate to be pushed (bottom)

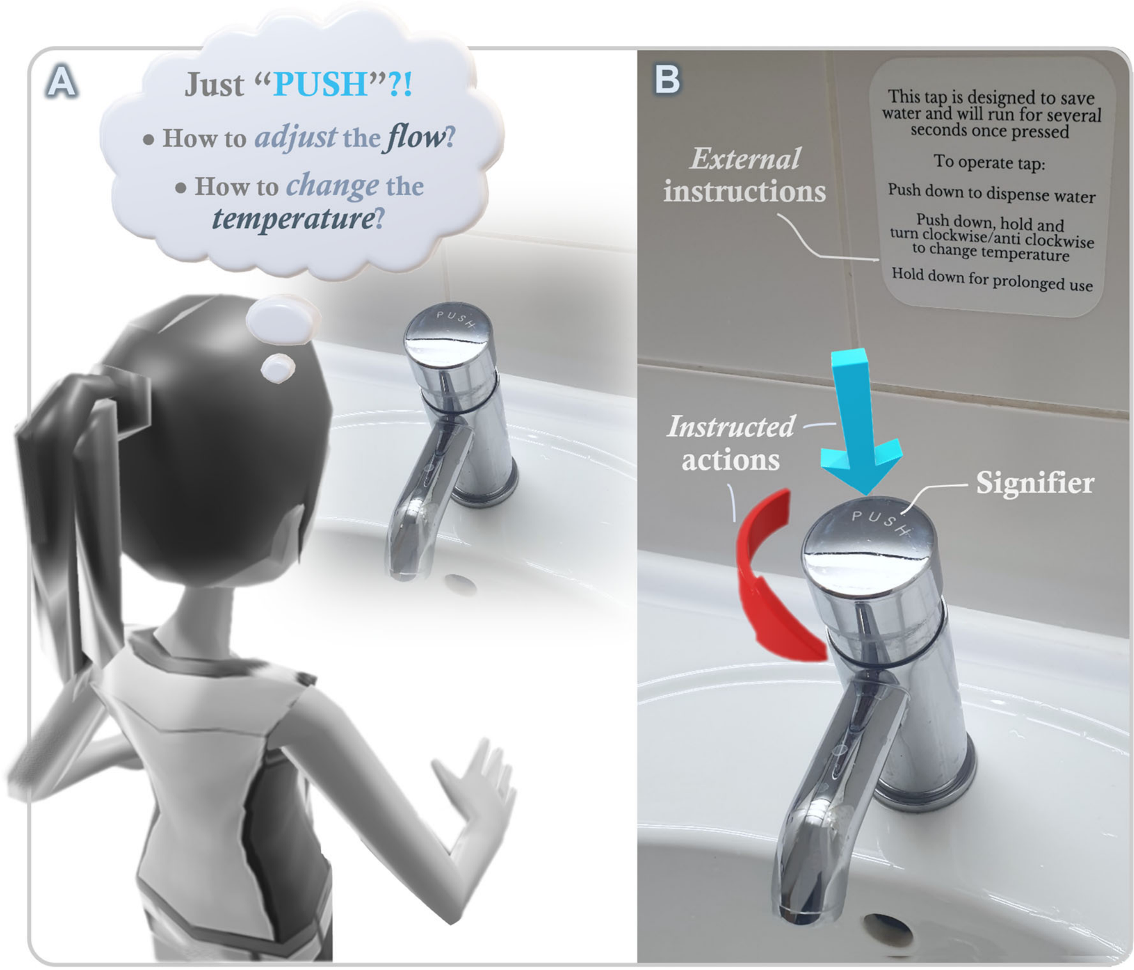

Fig. 8 **A** An uninitiated user trying to figure out how to operate a timed-flow basin tap. **B** External instructions need to be provided in order to guide the user on how to operate the tap

3.1 Timed-flow water tap design

Water taps and dispensers that are used in sanitary appliances (e.g. sinks, wash basins, and baths) come in various designs and with different operational mechanisms and user-interaction requirements.

Timed-flow taps (also known as percussion, non-concussive, timed-flow, self-closing, and push-down taps) are a class of taps that, once pressed down, operate and deliver a timed water flow and then stop the flow automatically. Timed flow taps, which are generally used in public toilets and commercial built environments, are designed to (1) reduce water and energy consumption, and (2) prevent flooding. Despite their potential advantages, timed-flow taps can be confusing for users if there are no accompanying instructions, because they generally do not offer sufficient affordances for appropriate actions.

As an example, Fig. 8A illustrates a young uninitiated user trying to figure out how to operate a timed-flow basin tap. The design can be considered minimalistic, compact, and perhaps elegant, while incorporating both flow and temperature adjustments using a single handle (or knob). Despite such desirable qualities in terms of both form and function, the tap design barely provides any effective affordances to help the user find out how to adjust the flow and temperature, as well as how to enable a prolonged water flow. Importantly, the textual signifier "PUSH" helps the user figure out how to get the flow started, but does not provide any other clues about the other operational features of the tap. Consequently, it becomes necessary to install 'external instructions' on the wall above the wash basin as designated in Fig. 8B.

3.2 Commuter train interior design

Designing useful and efficient train interiors is crucial for providing passengers with a satisfying onboard experience. This requires the integration of various products and services, which have to address a wide range of engineering and user-centered design requirements, in a highly-limited design space. In this section, we present three examples from various interior design features in a typical commuter train to investigate the position of affordances in competition with formal and functional requirements.

Commuter or suburban passenger rail transport services are chiefly designed for passengers in a seated position. However, designers need to consider the addition of standing passengers onboard on busy or special occasions. As the first example, we consider the orange objects attached to the headrest of the passenger seats, as shown in Fig. 9A. The existence of these features on only the outer edge of 'aisle seats' implies they are most likely to be used by standing passengers, and their concave geometry suggests that they afford 'gripping'. Importantly, unlike many other features of the train's interiors that are accompanied by signifiers or external instructions, these handles contain no other clues apart from their form-induced affordance.

As the second example, Fig. 9B shows the wash basin of the train's toilet with an integrated water tap, soap dispenser, and dryer. As can be seen from the figure, all the three services are accommodated in an area just above the basin, which is inevitably 'hidden' from most users' sight, mainly due to the need for extreme compactness. As a result, this design does not provide adequate affordances, and textual signifiers (i.e., the three words water, soap, and dryer) and symbolic signifiers (i.e., the arrows) are absolutely necessary to provide guidance for using the services.

Figure 9C(*a*), as the third example, depicts the user interface of an emergency call point in the train. In terms of form factor and geometric design, it bears a remarkable likeness to some antique wall-mounted telephone intercommunication (intercom) telephones. An example, namely the wooden intercom telephone GEC K7867[3] from the early 1900s, is shown in the upper part of Fig. 9C(*b*). In the lower part of this figure, a slightly different version of the telephone, namely K7866, is depicted, along with a picture from a popular British television series set between the years 1903 and 1930[4] [138]. As well as a likely source of inspiration for the designer, this geometric layout could function as a cultural reference to a vintage intercommunication system for some users.

Nevertheless, perhaps the most effective clue for a typical user to understand what the device shown in Fig. 9C(*a*) does is the graphical label representing the classic telephone handset. Besides, apart from the written instructions within the green area in the upper part of the device, there are other useful affordances integrated into the user interface which provide operational guidance as follows:

i. The user interface contains two distinct areas with circular patterns of small holes, designated within blue borders in Fig. 9C(*a*). The difference between the overall size and layout of these holes, which is due to the differences between the functional requirements for hearing and speaking, has also contributed to the affordances of this device. That is, there is a one-to-one mapping between these features and the patterns on the receiver and transmitter caps of the classic telephone handset and those of the vintage intercom telephone, as designated by single and double circles in Fig. 9C(*b*) and Fig. 9C(*c*), respectively.
ii. The transparent window of the flap provides sensory and cognitive affordances about the existence of a button under the flap.
iii. The classic, red push-button affords pushing (Fig. 9C(*d*)).
iv. The visible rotational hinges (enclosed by orange dashed borders in Fig. 9C(*a*)), which may remind the user of a door or piano hinge (Fig. 9C(*e*)), provides an affordance about the rotatable flap which can be pulled down.
v. The concave quarter-sphere-shaped part of the flap (enclosed by yellow borders in Fig. 9C(*a*)) is provided to accommodate the human finger(s), similar to many everyday objects such as the example depicted in Fig. 9C(*f*), which "*affords entrance by the hand*" and "*signifies a pull*" [118].

3.3 Automotive door handle design

In automotive design, it is known that certain practically-required components disturb the otherwise smooth surface of the vehicle. Importantly, they generate turbulence and energy-absorbing eddies which contribute to a form of aerodynamic drag commonly referred to as excrescence drag [139]. On the other hand, tactile experience is a quality signal when one deals with a car, which often starts with the exterior door handle of the vehicle. The 'feel' of the handle, along with the weight and sound of the door as it is opened and closed, signals messages about the quality, integrity, and safety of the vehicle [140]. From the viewpoint of the theory of affordances, apart from the apparent 'functional' affordance, a vehicle door handle provides an important 'emotional affordance'. As a result, particular attention should be paid to the design and manufacture of this feature in automotive exterior design.

An illustration of various types of exterior door handles of modern cars is presented in Fig. 10A. Among these categories, which are commonly named based on their opening

[3] *GEC K7866 and K7867 were manufactured by the British electronics and communications conglomerate General Electric Company (GEC).*

[4] *The television drama series was called "Upstairs, Downstairs", ran on ITV from 1971 to 1975.*

Fig. 9 Different features and user interfaces in an overground train. (**A**) Standing passenger handles. (**B**) Toilet wash basin with integrated water tap, soap dispenser, and dryer. (**C**) The user interface of an emergency call point in a commuter train

and closing mechanisms or the required user's action, the *pull-out* and *pull-up* handles have been the most common types in the past few decades. In the rest of this section, we examine the door handle design for three different classes of ground vehicles, namely passenger cars, passenger vans, and trucks.

3.3.1 Passenger cars

With the advent of electric cars, the automotive industry has been experiencing novel features and capabilities such as doors with electrically-powered mechanisms and innovative

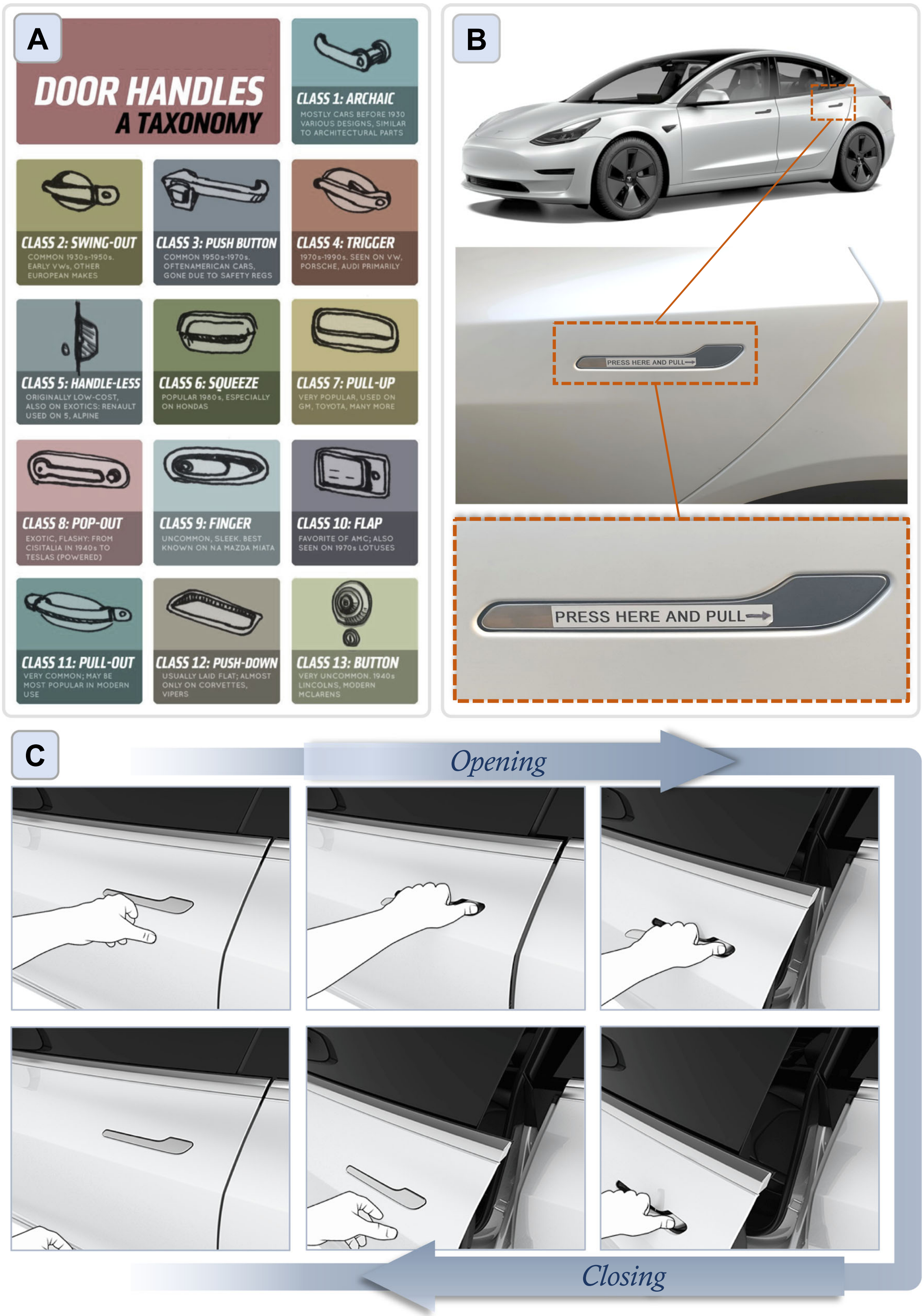

Fig. 10 **A** An illustration of various types of exterior car door handles (adapted from [142]). **B** The Tesla Model 3 and the close-up of its exterior door handles, where the owner has added stickers to the surface of handles to guide users on how to open the door. **C** An illustrated step-by-step guide of how to open or close the door from the outside (adapted from [141])

Fig. 11 Different designs for the door handles of passenger vans with different affordances. **A** Hyundai iLoad 2015. **B** Mercedes-Benz Sprinter 2021

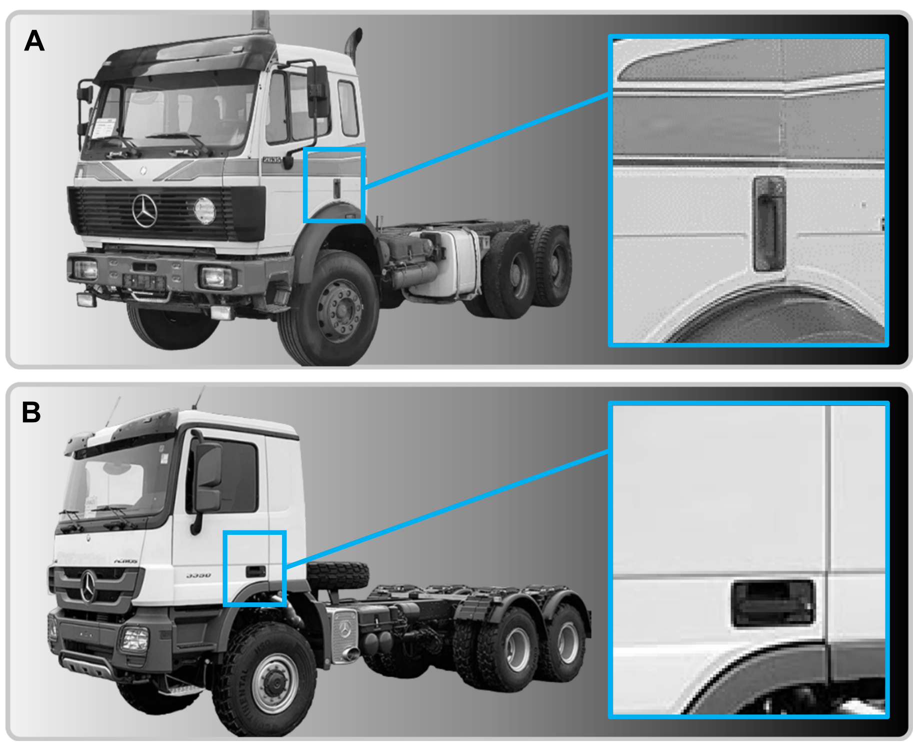

Fig. 12 Different designs for the door handles of Mercedes-Benz trucks. **A** Mercedes chassis truck 1993. **B** Mercedes Actros 3350-A chassis cabin 2018

handle designs. In this section, we examine the electrically-powered doors of Tesla Model 3 in terms of the three vertices of the FAF triangle, i.e. form, affordance, and function (Fig. 10B and C).

According to the owner's manual [141] of the car, to open the door using exterior door handles, users need to use their thumb to push the wide part of the door handle; the handle then pivots toward them, and they can open the door by pulling the handle or pulling the edge of the door (Fig. 10C). However, the handle design barely provides an uninitiated user with any effective affordances on how to open or close the door. That is why, in Fig. 10B, the taxi driver has added stickers containing instructions to the surface of the door handles.

It can be discussed that, while the flush design of the exterior door handles contributes to the function of the vehicles by decreasing the aerodynamic drag of the vehicle, and has visual appeal because of its simplicity and physical integration into the vehicle's body, it is a relatively poor design in terms of functional affordances.

3.3.2 Passenger vans

While designers often attempt to produce products and systems with proper affordances, other considerations such as economy of scale or styling may override design decisions. As an example, here we present different designs for the door handles of passenger vans which offer different affordances. For the first van depicted in Fig. 11A, two different types of door handles are integrated side-by-side into and unified by a visually continuous plastic housing, with each handle "*neatly signaling its proper operation* [118]". The vertical orientation of the handle lever corresponding to the sliding door signifies a sliding movement, while the horizontally oriented handle of the front door, together with an indentation (concave surface) that "*affords entrance by the hand*" and "*signifies a pull*" [118]. This design leaves negligible to no ground for users' confusion. On the other hand, the van shown in Fig. 11B has two horizontally oriented handles despite having two doors with two different mechanisms of closure/opening. As a result, in comparison, the first design (Fig. 11A) is appropriate in terms of affordances, while the second design (Fig. 11B) is inappropriate. However, when we look at the historical evolution of commercial vehicles, we can see that there has been a general trend towards replacing vertical handle levers with horizontal ones even when they do not provide the user with proper affordances (e.g., in the case of a horizontally sliding door).

3.3.3 Trucks

Another example is given in Fig. 12 where two Mercedes-Benz trucks with a 25-year age difference are depicted. As can be seen from the figure, the vertical handle of the older model was replaced with a horizontal one in the new vehicle. To understand this layout design shift, we analyze this problem from three points of view as follows:

I. ***Ergonomics:*** The vertical design is ergonomically superior to the horizontal design because of the following reasons:
   i. It is more compatible with the natural orientation of the human wrist (for the same reason that, in general, vertical computer mice are ergonomically superior to horizontal ones).
   ii. The pulling force of the user is effectively applied to the maximum distance from the rotational hinges of the door, enabling opening/closing with minimal force.

II. ***Aerodynamics:*** The horizontal design is aerodynamically superior to the vertical design because it has a smaller profile area.

III. ***Aesthetics:*** The horizontal design is aesthetically superior because it is aligned with the direction of the motion, and the body lines, of the vehicle, which evokes a sense of motion.

A comparative merit matrix for the door handle designs of the two vehicles depicted in Fig. 12 is presented in Table 1. As can be seen from this table, in this design case, aerodynamic and aesthetic considerations overruled the ergonomics ones.

In the next section, we further study the trucks' door handle design case and discuss the design decision considering the FAF triangle.

4 Discussion and conclusions

An affordance-driven approach to design weighs the appearance of clear user-interaction cues over functional and aesthetic considerations. This paper critically analyzed the concept of affordance in the context of industrial design and product architecture, where we particularly attempted

Table 1 A comparative merit matrix for the door handle design of the vehicles depicted in Fig. 12 based on the FAF triangle

Concept	Affordance	Function			Form
		User-experience level		System performance level	
	Usability	*Ergonomics*		*Aerodynamics*	*Styling*
	Perceptible affordances	Natural wrist orientation	Minimal actuation force	Minimal drag force	Emotional impact & aesthetics
A	✓	✓	✓	×	×
B	✓	×	×	✓	✓

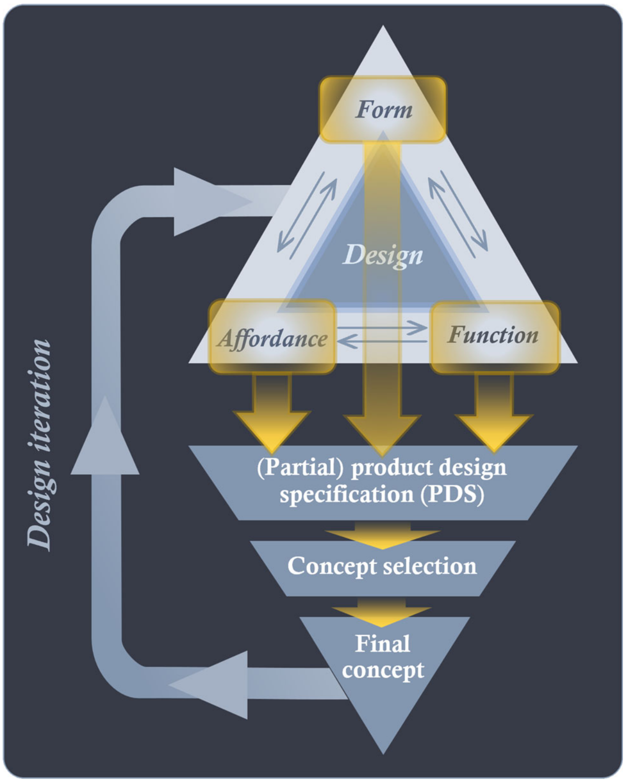

Fig. 13 Three fundamental concepts of design which contribute to the establishment and evolution of a partial PDS, the evaluation of different candidates, and the selection of the final concept in a typical product design process

Table 2 Criteria scoring matrix for concepts **A** and **B** evaluated against a set of five criteria $\mathbf{C_1}$, $\mathbf{C_2}$, …, $\mathbf{C_5}$

Concept	Affordance	Function			Form
		User-experience level		System performance level	
	Usability	*Ergonomics*		*Aerodynamics*	*Styling*
	C_1 (Interaction cues)	C_2 (Orientation)	C_3 (Actuation)	C_4 (Drag)	C_5 (Aesthetics)
A	100	100	100	30	30
B	100	10	50	80	70

to develop insights into the interactions of affordance with form and function. A comparative diagram was presented for Hartson's terminology versus Gibson's and Norman's terminologies using two industrial design examples. Furthermore, various industrial and automotive design examples were utilized to investigate the position of functional affordances in competition with other design objectives such as engineering, ergonomic, and aesthetic requirements in design decisions.

We proposed an approach to the synthesis and analysis of designed objects and systems in which three fundamental concepts of design, namely form, function, and affordance, were considered as the criteria with competing, and sometimes conflicting, requirements. It is important to note that such analyses can be linked to established frameworks for concept evaluation and decision-making in the early stages of the design process. More specifically, in order to make informed decisions in the design process of a product, we need to use a formal concept selection procedure to evaluate and rank the product design specification (PDS) criteria. Figure 13 depicts a proposed workflow in which the FAF triangle contributes to the establishment and evolution of a partial PDS in a typical product design process; it is followed

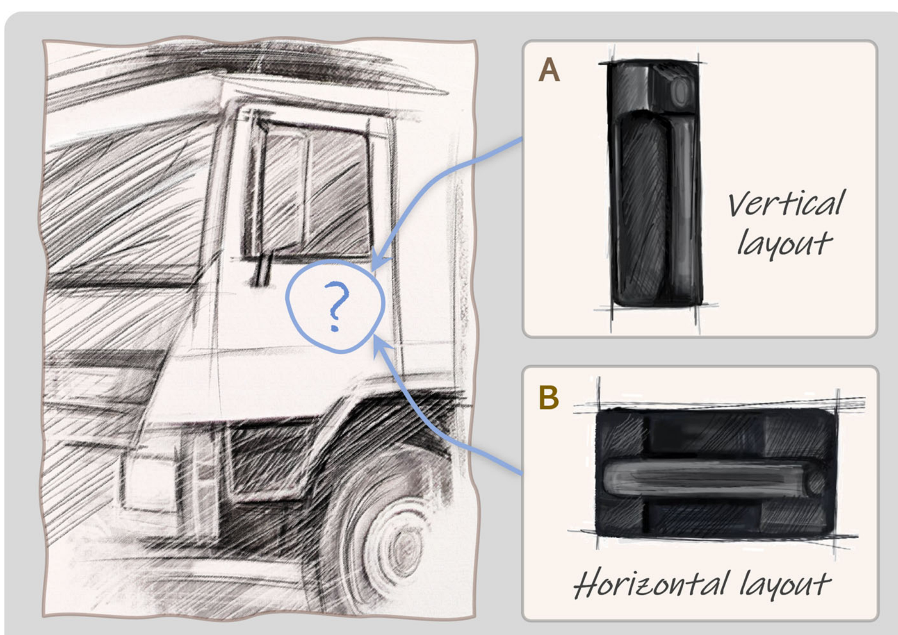

Fig. 14 Conceptual design sketches for the exterior door handle of a typical truck. **A** Vertical layout. **B** Horizontal layout

Table 3 The binary dominance matrix and concept selection worksheet (T = Total; R = Rank; W = Weight factor)

Criteria	$\mathbf{C_1}$	$\mathbf{C_2}$	$\mathbf{C_3}$	$\mathbf{C_4}$	$\mathbf{C_5}$	T	R	W	(*Weighted*) scores of concepts			
									A	$W \times$ **A**	**B**	$W \times$ **B**
C_1		1	0	0	1	2	3	0.2	100	20	100	20
C_2	0		0	0	1	1	4	0.1	100	10	10	1
C_3	1	1		1	1	4	1	0.4	100	40	50	20
C_4	1	1	0		1	3	2	0.3	30	9	80	24
C_5	0	0	0	0		0	5	0	30	0	70	0
Total						10		1		**79**		**65**

by a systematic concept evaluation and selection procedure to make the final decision.

To demonstrate this approach, here we again consider the examples presented in Fig. 12. Considering a typical truck, two conceptual design sketches for the driver door handle, i.e., a vertical layout versus a horizontal layout, are illustrated in Fig. 14. In this case, we have a set of five criteria against which each of the two concepts should be evaluated and scored. We consider a score between zero and 100 for each concept against each criterion, based on a subjective assessment [135, 143] of how well each concept meets each criterion. The results are summarized in Table 2.

Furthermore, we adopt the binary dominance matrix proposed by Pugh [134, 135, 143]. In this method, the criteria are listed on both the vertical and horizontal axes. Depending on the relative importance of the pair of criteria, as judged by the design team, a binary value of 1 or 0 is placed in each cell of the matrix. The binary dominance matrix and concept selection worksheet associated with concepts **A** and **B** are presented in Table 3, which suggests that concept **A** is more suitable than concept **B**.

Here we should mention an important limitation of the FAF triangle in the product design process. There are often many other elements that need to be considered in the establishment and evolution of a complete PDS; examples include manufacturing processes, production time scales and costs, and appeal to the target market. As a result, the FAF triangle should be considered a 'partial' contributor to the establishment of a PDS. That is why we have used the term 'partial' PDS in the flowchart depicted in Fig. 13. In other words, in a design project with a 'total design' [134, 135] approach, many other elements need to be introduced to the workflow to achieve desirable outcomes.

Acknowledgements The authors would like to thank Hyundai Motor UK Ltd and Kia Motors UK Ltd for funding this research project. They also thank Jason Torchinsky for the permission to reproduce his taxonomy of door handles.

Funding This research has been funded by Hyundai Motor UK Ltd and Kia Motors UK Ltd.

Availability of data and material (data transparency) Data will be available on request to the corresponding author.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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