How do Gestures Matter for Mutual Awareness in Cockpits? Disclosing Interactions through Graphical Representations

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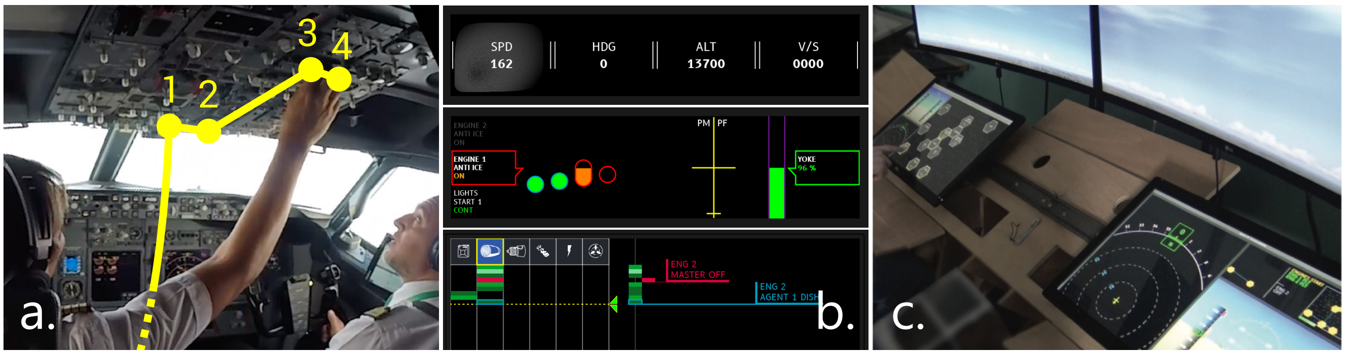

Figure 1: a.) a gestural flow performed by a pilot during a real flight (B737 aircraft), b.) 3 out of 8 alternative designs for the gesture view aiming to ensure mutual awareness among airliner pilots, c.) the cockpit testing platform with the gesture view (right).

ABSTRACT
This paper presents an approach ensuring mutual awareness among airliner pilots using touch-based interactions. Indeed, touchscreens are making their way into cockpits, but touch-based gestures are less performative than gestures on physical controls, and they are limited in aircraft for efficiency and safety reasons. To support a safer perception by the other pilot, we propose to supplement the perception of performed gestures with graphical representations. Our hypothesis is that representing the effect of gestures is more relevant than representing gestures themselves. We introduce our design choices to build the representations for mutual awareness based on an analysis of the activity and graphical semiology. We report results gathered from walkthroughs of the designs with airliner pilots. These results confirm that representing the effects of gestures is an efficient means for mutual awareness. Our work shows how pilots understand the effect of gesture both as a result and as an impression.

Author Keywords
Design; Mutual awareness; Touchscreens; Gesture representation; Collaboration; Critical context; Aeronautics.

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CSS Concepts
• Human-centered computing~ Visualisation design ~ Gestural input ~ Collaborative and social computing systems and tools.

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION
The integration of touch surfaces in airliner cockpits [1][29] aims to replace the current instrument panels that combine digital displays and physical controllers. Touch screens, besides their advantages to respond to the growing complexity of systems and to achieve lower costs, also allow efficient interactions for pilots, thanks to the direct manipulation of objects, interface plasticity or context adaptability. They enable information from multiple systems to be efficiently synthesized, filtered and dynamically layed out according to the flight context or pilot needs. Various issues related to touchscreens in airline cockpits have been addressed such as studies focusing on low sensory feedback and instability [13][22]. In this paper we rather address the impact of tactile surfaces on collaborative work and more specifically on mutual awareness.

An airliner is typically operated by a crew of two pilots: one, the Pilot-In-Command (PIC), is the captain, while the other is the supporting First Officer (FO). The cockpit is a specific environment where all actions to modify avionics system functions are distributed and accessible to pilot crew through gestures and vision [32]. This accessibility is achieved either by redundant information or by spatial ergonomics that bring the physical controls together in the centre of the cockpit. In the aeronautics field, mutual awareness is achieved when both pilot flying (PF) and pilot monitoring (PM), are able to fully understand each other's behavior and intentions, especially during degraded contexts [47]. The pilots' gestures fully contribute to mutual awareness through the form and dynamicity of their movements. However, touch-based gestures are less comprehensible than gestures performed on physical controls [12][19]. First, the display on a smooth surface together with the loss of tactile perception, force pilots to increase their visual attention [44]. Then, possible gestures are limited by flight conditions, including turbulence [18] [28], body fatigue [7] or the effect of gravity [4]. Finally, the dynamic display of touch interfaces, unlike statically distributed controls in the cockpit [32], significantly reduces the comprehension of the other pilot's actions, requiring a double check that the interaction is associated with the proper displayed objects.

Given the loss of visual attention, the limitations in feasible touch-based gestures and the increased difficulty of understanding the other pilot's actions, we propose an approach to supplement previous physical gesture properties through graphical representations that would provide an equivalent and sufficient information for mutual awareness. We carried out a design exploration based on the analysis of the pilots' gestures, and using graphic semiology, we designed graphical elements that represent the actions of a pilot on their colleague's screen in a Gesture View panel.

Two types of information, relating either to body language or interactions with the avionics system can be combined. We had to decide whether the improvement of mutual awareness should be based on representing the pilot's behavior or just providing better visualizations of the state of the aircraft resulting from the interactions on the avionics systems. Regarding behavior, litterature on gestures provides directions for understanding the major functions of gestures (deictic, ergotic, ...) [25][35][34], for designing comprehensible gestures [50], and for representing gestures [42]. However, through the study of the activity, design explorations and feedback obtained from pilots, we found that we may not need to mirror the gestures themselves to convey the information required for mutual awareness. A more efficient approach is to let a pilot perceive the *effect*, or the *meaning* of the other pilot's gestures, based on two understandings of the word "effect": as a *result* of the action performed, and as an *impression* made on perception.

The contribution of the article is twofold. Firstly, it provides a set of gesture dimensions relevant for representing the meaning of gestures for mutual awareness in a critical context [10], together with the graphical elements to be associated with them. Secondly, it identifies elements for a discussion on the principle of focusing the design on the effect of gesture instead of the gesture itself.

The paper is organized as follows. After reviewing the state of the art and a methodology section, we describe our observations and analysis of pilots' gestures during the cockpit activity. The two next sections provide a detailed description of the designs and of the pilots' feedback. The paper ends with a discussion on open issues and future work.

RELATED WORK

Our work is drawn from several areas: interaction awareness in the context of touch-based interaction and distributed collaboration, gesture-based awareness and gesture representations.

Awareness in collaborative touch-based interaction

Research work on the impact of touch-based interaction on collaborative awareness reports touchscreens being more efficient than IT mice [27] but also report that tangible interaction enables gestures that are more visible than touch-based gestures. For instance, some authors observed that the physicality of tangible tools facilitated individual ownership and announcement of tool use, which in turn supported group and tool awareness [46]. Equally, researchers noted that players were significantly more aware of other players' actions using tangibles than those using pure multitouch interaction, indicated by faster reaction times [16]. These studies both warn of a threat of multi-touch gestures for collaborative and workplace awareness [2].

Interaction awareness in distributed collaboration

Mutual awareness of gestural interaction in collaborative contexts has been addressed in various ways, depending on the configuration of collaboration in time and space [33] and on the type of synchronization within tasks. While pilots are co-located in the same physical space, their need in terms of awareness partly corresponds to remote collaboration since they interact on two different screens and must maintain their gaze in the direction of the plane's trajectory whenever possible. This distributed collaboration is close to mixed-focus collaboration, as described by Doucette et al [23], that happens when people divide labour, carry out assigned jobs individually, and then gather to merge their results.

Designing vs representing gestures for awareness

Our approach has to be distinguished from work where awareness is achieved through mirroring distant gestures on objects, and where gestures are designed or elicited for their qualities of collaboration enhancement. For instance, research on remote collaboration configurations [23] [36] introduces the principle of digital embodiments that are used to represent the remote gestures. In this direction, Kirk et al investigated existing taxonomies of gestures in social sciences [9] to enhance their digital embodiments, but finally provided their own more refined analyses of gestures to promote awareness (Flashing Hand, Wavering Hand, Mimicking Hand, etc). But their focus is rather to identify relevant gestures to be mirrored than to investigate how to represent gestures and their meaning to enhance awareness. Studies [43] regarding the impact of co-located interactions for mutual awareness might apply in the case of a single large interactive surface, as in ODICIS [1][8] or Avionics 2020 [29]. For such large surfaces, research work reports that using view portals, where a part of the user interface is duplicated to facilitate access and visibility, introduced new barriers to awareness, understanding, and coordination making it harder to see others' actions [45].

Gesture representation

While their objective is to help a user enact a gesture based on its graphical description, rather than to build dynamic representations for mutual awareness, McAweeney et al. [42] propose a framework to represent gestures for users, using new rules for gesture representations. Based on an analysis of drawings in the literature of guessability studies for gesture-based interaction, they establish a reference of the graphical elements that are commonly used, such as colors, arrows, shadows, texts, etc. to represent gestural dimensions such as time, position, posture, motion and touch. They also performed a user-centered guessability study to identify end-user preferences in the graphical representations.

METHODOLOGY

This section describes the design process, the workshops, the platform and the scenarios.

Design process

We established an analysis of pilot gestural activity based on the specialized literature, observations, interviews and workshop sessions with professional pilots. In particular, we observed the gestures of pilots in operational flight situations: in real conditions during two commercial flights in a Boeing B737-800, and, in the context of simulator-based initial training, during two flight sessions in an Airbus A320 simulator performed by two student pilots accompanied by an instructor. These flights, including scheduled flights, were fully filmed (8 hours of recordings) and the gestures, with their duration and associated controls, were annotated.

Workshops

Using graphic semiology, we carried out ideation workshops with product designers, graphic designers, engineers and researchers to produce ideas in the form of sketches (~ 200 sketches). We selected 2 ideas that we implemented as scenarios (see Table 1) using the Smala event programming language based on the djnn framework [14][15]. We conducted 3 series of 1 hour workshops with 5 professional pilots. The pilots recruited are experienced captains or first officers, qualified on Boeing B737-800, Airbus A320 or Beechcraft 1900D, and working in airlines such as Air France, Transavia, Twin-Jet or Volotea. One of the participants has the qualification to fly the A320 but was not on duty at the time of this study. During the first session we presented 2 designs (D1, D2) (see Table 2) based on scenario S1. Using the results of the first workshop series, we prototyped 2 additional designs (D3, D4) using scenario S2. Finally, to obtain complementary results, 4 designs (D5, D6, D7, D8) were prototyped based on scenario S3. The sessions were filmed (15 hours of recordings), transcribed (51 transcription pages) and analyzed using qualitative coding.

Platform and Gesture View

A wood-based prototyping and testing platform reproducing an airliner cockpit instrument panel in a simplified way (Figure 1.c) provided a coherent spatial arrangement of the instruments and the flight parameters display. It reproduces an ecological environment for work sessions with pilots.

We used two classes of scenarios during the workshops: one based on the overhead panel, which is used for adjusting the main aircraft systems: electrical, hydraulic, etc. (Figure 2), and another based on the Flight Control Unit (FCU) (Figure 3), which is a panel of buttons to change flight parameters (speed, altitude, heading and vertical speed) or engage the Auto-Pilots.

Overhead panel

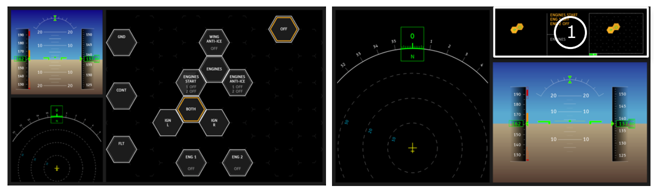

Figure 2. On the left PM monitor, on the right PF monitor with the Gesture View (1)

The designs D1, D2, D3 and D4 are composed of two interfaces, one for each pilot. In the left seat, the PM's touchscreen displays an overhead panel. In the right seat, the pilot flying (PF) sees on their screen a small frame, the Gesture View, reserved for the representation of the other pilot's gestures (Figure 2.b, top-right corner). This frame is located between the PFD (Primary Flight Display), the main flight instrument, and the window in order to be included in the pilot's visual circuit. The Gesture View is a fixed-path prototype controlled by the designer using a panel implemented in smala to run the animation. During the workshops, the professional pilot seated on the right (PF position).

Flight control unit

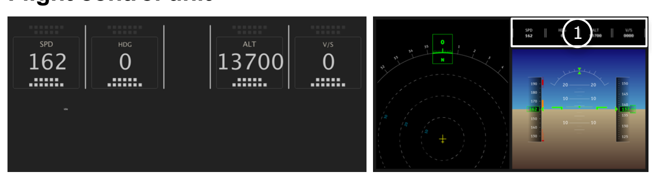

Figure 3: On the left the Flight control unit, on the right PM monitor with the Gesture View (1)

D5, D6, D7, D8 designs also include the two interfaces for each pilot. This time the PF sits on the left and the PM on the right. During the workshops, the pilot was seated on the right (PM position).

Scenarios

The designs are built on 3 scenarios (Table 1) based on different levels of mutual awareness. The (S1) Engines Start Switches Anti Ice scenario is a procedural flow controlling engine defrosting. We reproduced this standardized procedure in accordance with our observations aboard a Boeing B737-800. The monitoring pilot selects in this order: Engine ; Engine start ; ENG 1 ; ENG 2 ; CONT burner mode ; Engine Anti Ice ; ENG 1 ; ENG 2 ; ON ; Engine. It does not operate under any particular pressure, unlike the second scenario. Engine failure after V1 procedure (S2) consists of “memory items” (a sequence of memorised actions) which are applied whenever an anomaly is detected on an engine during the take-off phase. It is imperative for this situation to have a high level of mutual awareness. The problem occurs at the end of the runway and forces pilots to continue their take-off until they reach a safe altitude (400ft). In our scenario, engine 2 stops working: after seeing the problem and deciding to take off, once the 400ft has been reached, the PF is still unable to stabilize the aircraft, they keep their hands on the yoke and ask the PM to make the memory items: Engine ; Eng 2 ; OFF ; Full OFF ; Agent 1 Dish. The aircraft stabilizes and the scenario ends. Finally, the third scenario (S3) is carried out on the Flight Control Unit (FCU). The PF performs three adjustment gestures in the following order: speed increase; heading setup toward the Auto-Pilot; altitude increase.

Original Device	Scenario	Design	Type of gesture
Overhead Panel (OP)	Engines Start Switches Anti Ice (S1)	Honeycomb (D1)	Procedural flow (normal situation)
		Timeline (D2)	
	Engine failure after V1 (S2)	Bricks (D3)	Memory items (critical situation)
		Onion (D4)	
Flight Control Unit (FCU)	Speed, Heading, Altitude setting (S3)	Finger Shadow (D5)	Atomic gesture (normal & critical situation)
		Button Shadow (D6)	
		Blurring (D7)	
		Rim Texture (D8)	

Table 1: The 3 scenarios used for designs

PILOT GESTURES IN AIRLINER COCKPITS

Based on the litterature and our observations we describe the essential role of gestures in the collaborative activity of the pilot crew in the current cockpit, and how they ensure both an efficient execution of the numerous tasks assigned to each pilot and a high level of mutual awareness. It has to be highlighted that, given the paradigm shift from physical controls to touch-based interaction, changes will occur that may diminish the role of some gesture dimensions for mutual awareness.

A mainly collaborative dimension of pilots’ gestures

At any time during the flight, the two pilots (PF and PM) may respectively perform two different roles and associated tasks. The Pilot Flying (PF) is responsible for piloting the aircraft and controlling the flight trajectory. The Pilot Monitoring (PM) is responsible for monitoring the flight path, the energy and the system states of the aircraft, and for managing communications with air traffic controllers. The two-pilot crew of airliners requires precise task allocation to ensure optimal crew resource management (CRM). For this purpose, standard operating procedures are defined, based both on a strict separation of tasks and close collaboration between the two roles of PF and PM [21].

With regard to the use of cockpit space, the strict separation of tasks leads to a distribution of entry areas into the system, according to the role of the pilot and the different avionics systems designed by manufacturers. These are called "areas of responsibility" [24]. The layout of physical controls on the instrument panels requires the pilots to use ample gestures. Indeed, the architecture of cockpits and the task sequences often call for large gestural paths that can easily be perceived visually by the other pilot. When the action is less perceptible and action is crucial, the gesture can be accompanied by speech, as is the case for the engine igniter control on Airbus. When the pilot acts on the lever, they hold the physical control by grasping it from below and place their hand in a manner that maintains identification of the selected engine visible, and simultaneously states the upcoming action.

Regularly, and in particular at each new phase of the flight (e.g. climb, cruise and descent), the two pilots act jointly. They each have different tasks and associated gestures to perform in their areas of responsibility, but these pilot gestures are regulated by a precise sequence dictated by procedures or checklists. All operations must always be fully understood and shared by both pilots. If they do not directly monitor the other's work, they must constantly evaluate the other's actions to sequence their own tasks, anticipate or verify the progress of procedures and flight and anticipate possible technical risks or human deficiencies. The gestural sequences they perform are an essential aspect of mutual awareness between pilots.

The intentional dimension of gestures

A first fundamental aspect of the gesture performed by the pilot is its intentionality. The pilot acts on the avionics system parsimoniously and aims to perform an action as soon as they places their hand on a physical control. The critical context requires pilots to measure their actions. They cannot change a value or function without first assessing the safety impact of their actions. Intentionality is thus an essential notion of the gesture, for the performance of the crew's collaborative work and therefore for mutual awareness. The intention must be shared and consequently visible. The gesture, through the visual force of its physicality and movement, is a natural medium to inform the crew.

Atomic or sequential nature of gestures

A gesture considered as an isolated element is traditionally known as an atomic gesture [17]. In relation to the aeronautical context, it may be described as a body movement producing a single interaction on the avionics system. Nevertheless, it is interesting to note from our observations that this atomic gesture is always part of a procedural flow. There is no isolated interaction. Pilots perform gestural sequences in accordance with protocols or procedures defined by airlines and manufacturers. They are known by every pilot. Thus, regular procedures are repeated with each flight and are skillfully mastered. In contrast, emergency or critical failure procedures require pilots to be more attentive and involve less fluidity of movement.

Spatial identification of controls targeted by gestures

The layout of the physical controls and information in the cockpit allows visual and gestural access to be shared by both pilots. In addition, since the pilots are seated, they are required to complete gestural paths of variable length to reach the control panels. These paths are automatically perceptible by the entire crew. As the pilots have a body knowledge of the location of each cockpit element, they are able to perceive at any time which object is operated by the gestures of the other pilot. It has to be noted that this function and dimensions of gestures are closely related to the physical setting of controls in the current cockpit, so that their relative importance may change in a touch-based context.

Temporal dimensions of gestures

Temporal dimensions of a gesture are important to ensure mutual awareness in cockpits. They firstly concern the decomposition of a single gesture in successive steps: body movement towards the target control, gestural preparation or anticipation, activation of the control, and possibly final manual verification of the action. They also relate to the overall path and rhythm of the gestural flow. The perception of these successions, rhythms or summations of gestural durations, informs the pilot crew of their own performance. Above all, the pilot will be able to voluntarily modify the gesture fluidity. They may act on the overall rhythm of the flow, or caricature certain parts of the gesture, for example by marking intentional stopping times during the preparation of the gesture to provide information to the other pilot.

Gestures as a shared information medium

In addition to performing gestures to complete an action, the gesture is an important medium of information. When the auditory canal is overloaded, the pilot informally uses the semiotic function of gestures to communicate in the cockpit. For example, there are many "yes" and "no" gesture signs or the mimic of an action that allow pilots to coordinate or check the preparation or execution of an action silently.

The gestures also inform the crew about the pilot's behavior or condition, first of all by the action taken, but also by the singularity of the pilot's movements [26][3]. For example, they may indicate a state of fatigue, a state of stress or nervousness, or a state of frustration. This information is crucial for mutual awareness and therefore for safety. If the pilot sees fatigue or anxiety in their co-pilot, when they should be in charge of performing the landing, they can propose to reverse the roles and perform the action.

DESIGN

Given the needs of the activity in the touch-based context that is targeted in this paper, we seek to minimize the cost of controlled perception, i.e. the time required to read information. This is why we aim to produce a pre-attentive system [48], where information is identified and understood almost immediately (<250 ms) by the user. A pilot can thus at a glance, check information on the gestures and actions of the other pilot as when using physical gestures. To design suitable visual representations, our approach is informed by the Bertin's work on graphic semiology [5][6], which aimed to produce pre-attentive systems by combining graphic variables on a 2D plane [5]. Recent works such as Visual scanning [20] or dynamic representations [31] offer methods for the theoretical analysis of graphical designs, based on a set of elementary perceptual and cognitive operations, which make it possible to both characterize and think about interactive representations. *Semiology of Graphics* is based on three elements: invariants, components and graphics variables. In the following, as illustrated in Table 2, invariants are the 9 dimensions of gestures we have selected as relevant (lines in Table 2). Components are the elements that compose an invariant, and graphic variables are purely graphical, they are the graphic choices associated with a component. For instance, the *status* invariant has two components: ok or not ok, and its associated graphic variable is the (colour) hue. For the *time&rhythm* invariant and its duration component, several graphic variables have been used, including size, luminosity, animated texture, and animated blur.

To build designs, we used as invariants some dimensions from McAweeney: *location*, *time & rhythm (time)*, *move*, *and identification (touch)* [42]. Two of these dimensions, *location* and *move*, were deemed irrelevant from the first workshop on touch-screens, as explained in the Results section. This confirmed our initial intuition that the *posture* dimension from McAweeney could be discarded. Indeed, the mirroring of the interface with the hand or fingers [45] is not relevant in the cockpit context. Pilots are not expected to learn new gestures with the proposed representations, as in McAweeney, but rather to perceive actions' results with respect to the system state. Next, not representing the hand enables to convey more abstract meanings related to both formal and informal communication. Finally, abstracting the morphology allows more flexible designs in upcoming touch gestures. We added five dimensions to McAweeney's: *intention*, *trace, status, completeness*, *role*, taken from the observations of the pilots' actions presented in the previous section. Finally, we have added the *role* dimension since there are designs where the two pilots are represented simultaneously.

The *location* components are the coordinates of the gesture on the surface. *Time and rhythm* is based on the time markers of a gesture and its level of evolution in relation to a set of gestures, for example a flow procedure. *Move* refers to the movement of the gesture in space. As described by Cirelle et al [17] *move* happens in 2 levels: either as an atomic gesture, or as a sequence of atomic gestures. The latter indicates the movement of the hand in space between each gesture to produce several interactions. The *intention* refers to the aim of the gesture, such as selecting a function or a cross-check. The intention is significant in a collaborative setting, as a meaning of the intended gesture that can be perceived by the other pilot. The *identification* informs the pilot about the actual object being handled. This is what allows the pilot to identify the selected function in an unambiguous way. The *trace* allows the flow of actions performed to be followed or

DIMENSIONS OF GESTURE	GRAPHICS VARIABLES PER DESIGN							
	D1 Honeycomb	D2 Timeline	D3 Bricks	D4 Onion	D5 Finger Shadow	D6 Button Shadow	D7 Blurring	D8 Rim Texture
G1 Location	position				shape, position	shape, hue, position		
G2 Time & rhythm	size, value	shape, size	shape, hue, value	value	texture, animation		blur, animation	
G3 Move	shape, size		position	position	position, animation	position, animation		position, animation, opacity
G4 Intention			hue, text	hue, text				
G5 Status	hue	hue	hue, text	hue, text				text, hue
G6 Identification	shape, text	text	shape, hue	opacity	text, shape	text, shape	text, blur	text, position, shape
G7 Trace	opacity	animation	gestalt	gestalt				
G8 Completeness	saturation	hue	shape, hue, gestalt	gestalt, hue				position, shape
G9 Role		shape, hue		shape, hue, orientation				

Table 2: Identification of the graphics variables used for each of the eight designs (columns) and their correspondence with the nine dimensions of the gesture (lines). The visuals of these graphical variables are schematized.

to be performed by the pilot (as in the Guitar Hero game). The *status* is an information on the level of success of an action. *Completeness* provides information on the end of a gesture or sequence of gestures. At the atomic gesture level, the completeness information may come from the end time marker, while, for the sequence, completeness is information on the last action. Finally, the *role* makes it possible to distinguish the actions of each pilot when they act together on the system.

We selected Jacques Bertin's original variables but we chose to replace the color and value variables with the CIE LCH system (Luminosity, Chroma, Hue) in order to be more attuned to a digital display. Our visual variables are: position, size, shape, hue, saturation (Chroma), luminosity, orientation, texture. To express dynamicity, we added Wilkinson's variables: opacity, animation, blur, and text [49].

Design 1: Honeycomb

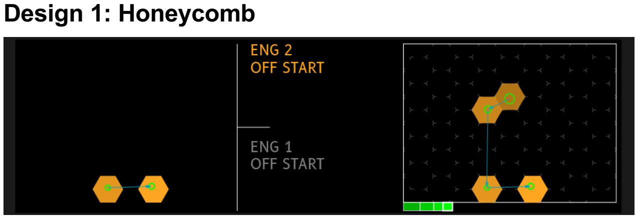

Figure 4: a sample of displayed graphical représentation from the *Honeycom* design (D1)

This is the first graphic presented to the pilots. It is broken down into two parts (see Figure 4). The current gesture is represented on the left. On the right, we represent the entire procedure flow so far. We have chosen this segmentation because it offers two levels of reading, the last gesture and a synthetic perception of the progress of the procedure. When the PM selects a menu or a function on the overhead panel, two hexagons are displayed on the left side with its name (e.g. ENG 1) and its state (e.g. ON ANTI-ICE), indicating the preceding and current finger positions. A circle also appears under their finger. On the right side, the same hexagons are added to the flow, and a new rectangle appears below the procedure flow. Circle and rectangle sizes increase according to the duration of contact. The state color reflects the status of the touch gesture, either green for "ok" or red if a problem occurred in gesture recognition. Each time the PM selects a new function, a new circle and a new rectangle appear in a similar manner. Previous function names are moved down and their hue are removed. Any move between touches is represented by a blue arrow. We chose the arrow shape because it is the best way to immediately understand the movement [42], and, as we have several gestures to represent, targeting the center of the circle makes pre-attentivity easier [5]. In the flow on the right, gestures hexagons lose one saturation level in turn. We associated the saturation with the graphical persistence because this graphical variable enables an ordered and selective readability [5]. When the procedure flow is completed, the hue is removed for the whole representation.

Design 2: Timeline

This second design (Figure 5) introduces the aeronautical notion of cross-checking with the actions of two pilots shown together on the same screen (PM on the left, PF on the right). Expected gesture flows, known by the system, are displayed as empty circles, on the left side for the PM, on the right side for the PF. Empty circles have a blue hue outline for the PM

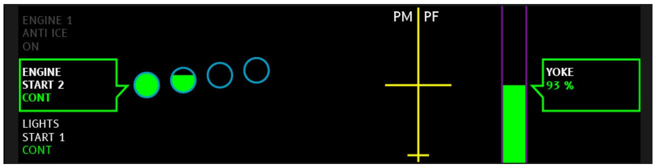

Figure 5: a sample of displayed graphical représentation from the *Timeline* design (D2)

and an empty square with a purple hue outline for the PF. The sizes of circles and squares were defined by an average duration according to our aeronautical observations. When one of the pilots touches his screen to activate a function, the corresponding circle or square fills up. Again, the color defines the status of the gesture, green by default. If the pressure is too long, the color turns to orange, with a red outline, and the shape turns into an oblong shape. Three items of text represent the previous, current and next functions to activate, the next one is without hue. The current function is highlighted by a speech balloon, the speech ballon color being again associated with the status, and the tip pointing to the current time, as is the case for the plane in the middle. The shapes move from top to bottom following the flight steps (*"as in Guitar Hero"*, says a pilot). The shapes of a procedure flow are positioned close to each other, in order for the pilot to immediately identify relations between gestures, applying the proximity law of gestalt theory [37]. The pilot may activate a function that is not expected in the standard procedure, a new empty shape appears accordingly.

Design 3: Bricks

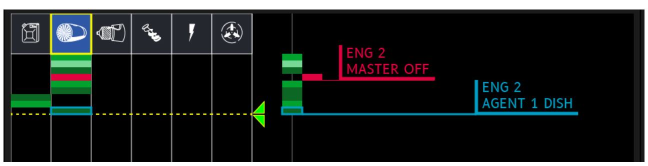

Figure 6: a sample of displayed graphical représentation from the *Bricks* design (D3)

Unlike the *Honeycomb* design, in accordance to results from pilot the *location* dimension and the *move* dimension of the gesture in the *Bricks* design (Figure 6) are not associated with its actual positions on the overhead panel, but, on the x axis, with columns associated with system pages (referred to through their pictogram), in a pre-attentive mode. Again, the color informs of the status of the information taken into account by the avionics: green or red if an "error" occurs; blue informs the PF that a validation is required (cross-check). The saturation variable informs the pilot about the time required to perform the gesture; the longer the gesture the lower the saturation. For an atomic gesture, this information is not significant. Thanks to the laws of gestalt, pre-attentive perception allows the pilot to discern the rhythm of the other and thus identify information such as fatigue or stress. For example, if all actions are quick when the situation requires restraint, it may indicate to the pilot that it is necessary to engage in a dialogue with their colleague about the situation.

Design 4: Onion

Figure 7: a sample of displayed graphical représentation from the *Onion* design (D4)

The fourth design is inspired by the laws of gestalt. We wanted to discuss a synthetic vision of the information with the pilots. The six systems (Figure 7 on the left) are equally distributed within a circle, and are indicated by a pictogram and a legend. The gestures are represented by circles. Each successive gesture is accumulated around a point. The position of the small circle in the surrounding one is updated with each new gesture placing itself in the triangle associated with the system in which the gesture took place. To highlight the function of the last gesture performed, its corresponding system pictogram is displayed while the others have their opacity reduced to 20%. With each new gesture, a new circle appears with a diameter greater than the previous gesture. Once the gestural flow is completed, the diameter of the last gesture fills the surrounding circle and visually announces the completeness of the flow (G.8,D.4).

Design 5: Finger Shadow

Figure 8: a sample of displayed graphical représentation from the *Finger shadow* design (D5)

The fifth design deals with the singular aspect of the pilot gesture that is involved when specifying a flight parameter such as speed or heading to the auto-pilot (scenario S3). Indeed, we decided that the proper dimension to identify what a pilot could interpret as an actual physical action, with its material form, as opposed to information coming from the system, would be the touch of the fingerprint with its shape and own dynamics. When the PF touches the Flight Control Unit, two graphical elements appear: the origin of the contact point represented by a circle and a rectangular shape composed of textured grain which identify the avionic function subject to modification. We chose to associate the contact duration with an animation to trigger a graphical persistence for the pilot. Indeed, the combination of an animation with an opacity variation has been described by [30] as an effective means to show time progression for an object. When the contact time extends, the circle size increases and the texture of the rectangular shape appears to disperse. Four shapes are possible according to the finger position on the FCU screen. Their orientation is differentiated by the corner form. As shown in Figure 8, the PF has touched the lower-left zone.

Design 6: Button Shadow

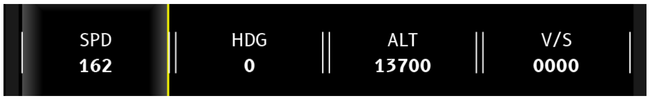

Figure 9: a sample of displayed graphical représentation from the *Button Shadow* design (D6)

The graphic representation of the sixth design is a critical proposal in relation to the *Finger Shadow* design: the gesture is no longer represented as a gestural imprint, it is only inferred. This is a more abstract level of representation: the pilot must know how the system works in order to obtain a cognitive representation of the gesture behavior. When the PF presses the FCU (Figure 9, left), two elements appear. The first is a rectangle allowing the co-pilot to identify the function subject to a status change. Corners of this rectangle take a gray scale to highlight the function in relation to the background. The contact point is suggested by the emergence of a yellow line on the edge of the nearest rectangle.

Design 7: Blurring

Figure 10: a sample of displayed graphical représentation from the *Blurring* design (D7)

The seventh design explores the blur graphical variable. Through animation, we use blur to try to deepen the visual information. When the PF selects a function on the FCU, the other functions gradually become blurred (on the right part of Figure 10). We used animation of blurring because we believe that it will be a natural guide to focus the gaze.

Design 8: Rim Texture

Figure 11: a sample of displayed graphical représentation from the *Rim texture* design (D8)

In the eigth design, when the PF slides down, the selection mode is activated. This mode allows the pilot to change the parameter's value, which is achieved by a swipe to the left to decrease the value or to the right to increase it. We chose to use texture (Figure 11, left) as graphical variable, inspired by the current FCU notched buttons. Indeed, each function has a different haptic perception. In addition, symmetrical shapes have been selected that can be cut in half to show a direction.

RESULTS

In this section, we describe the insights gained during walkthroughs with pilots. Here, our intention is not mainly to evaluate each design, but rather to gather and summarize important lessons learned from this design exploration. For this reason, insights may either be directly related to the components described in the Design section, or drawn from the analysis of the transcribed sessions. Designs involved in the pilots' feedback are referred to by their number (D1, D2, see Table 2) and pilots have been anonymized as P1, P2,...

Identification of implied system without spatialization

A clear outcome of the work was the need for a precise identification of the impacted systems. In fact, interactive screens render obsolete the spatial learning of the gesture flows performed through physical moves, and provide a simpler means of achieving the same result: "*about this loss of spatiality, what you can do is just put a line and say: 'it touches the engine part*'" [D1.G6, P2] or: "*so what would be nice is to have the name of the checklist, it allows me ... I'm piloting... and I see you have started the checklist I called.*" [D3.G8, P4]. Therefore, the *location* and *move* dimensions of gestures were clearly deemed unuseful. Further, the ability to unambiguously identify the involved parameter in the FCU scenario (S3) was even described as so critical, that one pilot found that showing hesitation of the finger between two buttons was irrelevant: "*Having only one edge, it's half focused. Something's going on here, but we have to wait.*" [D6.G1, P5].

Completeness

Representing flow progression emerged as an important need. The pilots commented in particular on using alignment, filling and colors for this purpose.

Alignment

Significantly, the pilots advocated the use of alignment. This interest can be related to the pre-attentive concept of the *dark cockpit* in Airbus design, where dark means that everything is satisfactory, and nothing is left to be done. Here, it is the alignement of each item in turn that means completion, in accordance with the Gestalt principle of *continuity*, whereas a shifted item means that there are still actions to be performed. For instance, a pilot suggested changing hexagons into squares so that they can be aligned together: *"The idea is to place the counters in such a way that graphically you see that everything is aligned. You know everything was actually done."* [D1.G8, P4]. This fostered the design of alignments in D3 and D4 for the next series of workshops. He also suggested that having buttons dynamically aligned rather than having statically placed physical buttons would be an advantage: *"Because in fact we memorize a shape because the buttons are there but if we could move the buttons it would be wonderful. We'd line them all up. So that the buttons change places according to the failure."* [D1.G1, P4]. In contrast, omitted actions, *"open items"* [D1.G8, P2], or actions still to be done are highlighted by being shifted or marked through a color, adopting this suggestion from one of the designer of the team: *"You'd rather have a kind of line where for example if everything is good, everything is green and then if I have one that's not good I'm going to have a red that stands out."* [D3.G8, P5].

Filling

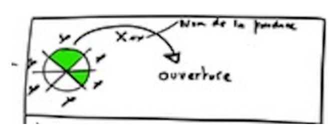

Figure 12: Sketch illustrating how filling expresses completion.

A pilot suggested to enforce this graphic choice through a variant of the *Onion* design (Figure 12): *"It is the the pie that fills* *up for each expected item and at the end you have the pie, like in Trivial pursuit. You see, because the circle inside a pie doesn't mean anything to me. Since it doesn't make sense because everything is full but you haven't yet done an APU, nor an Air Bleed for example."* [D4.G6, P4].

Colors

Using the green color to highlight completion was appreciated, in accordance with the current color coding standards in aeronautics. However the use of a symbol was prefered to a yellow outline: "*I really like the American symbol, you know, the little V. You see at the end, the little check.*" [D3.G8, P4] or the use of a progress bar [D3.G8, P1].

Time dimensions in mutual perception

Pilots had several comments on time, either related to the perception of objective time elements, such as duration, the past, or as a perception of things through more subjective time dimensions, such as speed, delay, regularity, rhythm, control, hastiness, smoothness, or cautiousness.

Duration

Designs of the first category, and in particular of objective duration, were often criticized as irrelevant for awareness: "*knowing precisely how long he has pressed, with hysteresis, all that, that, honestly, that has no operational interest*" [D1, G2, P5]. As a result, encoding the duration of a press in the size of a circle was not considered to be beneficial: "*the size of the circles, for me it is information that loads the display... for me frankly superfluous*" [D1.G2, P5]. In fact, perception of duration is also subject to individual and contextual perception. Highly stressful conditions sometimes lead to losing a sense of time, as for P1: "*sometimes you can have an engine failure at takeoff [...] and for 3 minutes you look for [...] and you don't understand, [...] and then: 'the gear hadn't gone down!' even though you've had the alarm yelling for 3 minutes. You see the notion of time you lose it.*" [D3.G2, P1].

Regularity

Regularity in a sequence of actions is meaningful [40]: "*he will touch one or two buttons at the top, his hand will go down, he will touch a button here with the same rhythm"* [D3.G2, P2] or: *"you've worked on it dozens of times with the simulator... with your colleague you find it, it's like music*" [D1.G2, P2]. This regularity was emphasized as bringing information about the other pilot being well or in control: "*And that tells me, I know where you are at, that everything is going well in the checklist process and that's what matters to me.*" [D3.G2, P4]. This also may highlight a break in the sequence as a problem: "*if after 30 seconds I see that the flow is not finished*, *I will ask him what he is doing*" [D1.G2, P5]. To express regularity, the *Bricks* design was considered more relevant than the *Onion*: "*I find [D4] less explicit than the previous one [D3]. Because in fact, in your head, an action is going to be a sequence, the fact that 'tac tac tac tac tac' it's piling up. Well [showing D4], it's true that... well*" [D3.G7/D4.G7, P4]. The *Bricks* design creates empty areas which allow the columns to be clearly dissociated, and this may be explained by Gestalt laws where the foreground is highlighted against the background.

The past

Pilots considered graphical designs of past actions and gestures (G.7 mainly D1, D2, D3) as rather irrelevant: "*once it's done, uh... we don't care about the past*" [D3.G8, P4], except if something went wrong, which is in fact made more noticeable within a regular sequence: "*On the other hand, you will be alerted if the guy skips an item and one is missing. If he jumps it, there [pointing to his screen] it's interesting to have a trace and if there's an explanation, we have to discuss it*" [D3.G7, P4]. Not too brief animated traces of the last gesture may, however, be of interest in the event of temporary visual inattention: "*You have four squares, right? I think it's nice [...] I still have a reminder of what it was like, where it was [...] suppose I have a little bit of inattention so you come back into your visual circuit from time to time, so your button musn't be a flash all the same.*" [D5.G2+G7, P3].

Control

Stress is "*felt through actions that are not fluid*" [D1.G2, P2], so that speed has to be interpreted within a flow: "*And above all, the speed of the movement can mean a lot, either that there has been a moment of ease, or assurance and it goes fast, or that there is a moment of stress.*" [D8.G2, P2]. A little cautiousness might be expected for irreversible actions, and this can be felt via a slight pause in the flow, which may be represented in a design by saturation: "*It's going to go very fast in parts of the flow because he knows it, then there's going to be a call for reflection... ah yeah, hop... and he finishes.*" [D1.G2, P2]. In the *Finger Shadow* design, it is the graphical persistence of the fingerprint that conveys a pause: "*I find it especially good to know that the other person can keep pressing... and therefore that he has a doubt, and that he does not immediately go for a value*" [D5.G2, P2]. An unexpected delay in a flow differs from expected cautiousness: "*if there's anything that lingers, you know it lingers*" [D3.G2, P4], and the pilot suggested making the area blink in such case: "*if after 3-4 seconds, the system has seen that you haven't done it yet, what interests me is that it flashes, telling me that it's taking time*" [D3.G5, P4]. *Button Shadow* design was seen by a pilot as potentially indicating a hesitation or even a mistake with respect to the targeted parameter area: "*the interest compared to the other [D5] is ... 'but what is he doing? Doesn't he know what he's doing?' Whereas on the other representation it was binary it's one or the other...*" [D6.G1, P3].

Awareness and coordination levels in collaboration

Two types of awareness can be distinguished: one that is based on feeling or having a sense of presence and that some activity is going on; the second is a more formal awareness required for safety, where information that the situation is running smoothly is built from controlled procedures using vision and/or oral communication.

Awareness through expressive gestures and rhythms belongs to the first category but also has an impact on safety, as potentially indicating the condition of the other pilot: "*What I actually find good is without having to look at the colleague to see if, first of all, he is there. So in terms of incapacitation it's very good information*" [P5], confirmed by another pilot: "*as captain, I find it interesting for surveillance purposes*" [D1, P2]. It may be considered as intrusive: "*... a little intrusive maybe. It shouldn't become a means for tracking*" [D1.G2, P2]. In fact, pilots sometimes preferred a more abstract or approximate representation such as a rhythm, or even just knowing which system was impacted by an action, rather than the exact function: "*I saw that you acted on the fuel, so a priori you probably cut* *things, [...] and uh for example there, I think it's electricity, you may have connected generators or things like that*" [D3, P1].

With regard to awareness within formal coordination, pilots appreciated being able to interact directly through the Gesture View, and thereby reducing the need for oral coordination. They also liked the possibility of performing coordination tasks without relaxing visual attention, and keeping track of these tasks: "*here's the thing, when you have a confirmation to do, that's it, 'tchouk'. And if you want to keep your traceability, there it would be marked confirm and once it's confirmed you can imagine it turning blank. So, let it stay to say 'it is confirmed'. You see, because when you read the memory item again, you know you did the thing right, and now it's really a crew job."* [D3.G7, P4]. This gives pilots an additional degree of awareness through shared situation awareness (SSA) [38] where both are aware of the state of the system and know they share this knowledge.

Finally, all the pilots were in favor of being able to maintain their visual attention looking forward, at the price of a lower mutual awareness via direct perception [45]: "*I don't need to take my eyes off my trajectory, and at the same time I see that my checklist is progressing. So I think it's great.*" [D3, P1]; "*First of all I can see right now where he has his hand without necessarily having to turn my head [...] it interrupts me less*" [D5.G6, P3].

Materiality

The pilots commented on the designs which bring details to convey more "materiality", for instance highlighting the rugosity of a button (D8), the shape of the finger (D5), or a perceptual nuance in the colors (D1, D3, D4).

Several pilots liked the *Finger Shadow* design: "*Yes, it really represents the finger that is pressing, more than the conventional colors of the thing that would be like that, it attracts the eye more I find yeah... on a movement...*" [D5.G2+G1, P2+P3]. The *Blurring* design triggered two opposite feedbacks. For some pilots, *Blurring* efficiently reflected a mechanism of visual perception: "*Yeah, the Blurring is not bad... because as you say, it's true that your eye ... the further away it is, the blurrier it is [...] you can really play on values, so in my opinion you can't put two hundred values of blur, that would be too much. But maybe with a dozen or so... you see... and that's ten values. It's still huge, though, ten values and you... and it's really very natural. I think everyone would perceive that quite well.* " also explaining that: "*in the end the color is soon aggressive*" [D7, P2]. His colleague expanded on this comment, highlighting progressivity: "*as soon as you finish this one [speed] and you switch to another one, it gradually blurs, the other one becomes super clear, and so you have a super progressive change*" [D7, P3]. However, another pilot rejected *Blurring* as dangerous since it prevented the free access to information. As a pilot said: "*In terms of information, what is intolerable is not being able to access something. You understand what I mean, when you're in a cockpit, you may not be able to display everything, but you have to be able to access it. What's really annoying is when you can't access it. You're not supposed to know everything, but you're supposed to be able to find everything.*" [D3, P2]. The *Rim Texture* design also involved materiality and perception, but it proved irrelevant. The imitation of the tactile granulate of the notched buttons with tiny graphical shapes, aimed at differentiating the knobs, was too small to notice: "*I'm not sure it changes much, but what can be interesting is that when you scroll it down, we've got a trend indicator: increase, decrease.*" [D8.G3, P3]. Finally, since colors are a highly codified system information, providing color gradients or shades must be avoided: "*I would rather see some ON OFF instead. Because now you see how it's not very clear the opacity gradient, it would have to be more marked*." [D1.G8, P5].

DISCUSSION

The study clarified the choice to represent gestures or the *effect* of gestures. Pilots confirmed that representing objective components of gestures, let alone the hand or fingers, had no operational interest. The spatial form of gestures to identify actions was also deemed obsolete with the advent of flexible displays. The study also confirmed that the representations of effect supplied to the pilots may be either result-oriented, containing systems' formal feedbacks, or impression-oriented, with subjective and perceptual elements. Impression-oriented representations were recognized as relevant, in particular to enhance mutual awareness in non nominal aspects. These includes graphical representations that convey regularity, error, reflection, hesitations, together with graphical elements conveying materiality, such as displaying a fingerprint. The results also lead to a positive conclusion on combining impression-oriented and result-oriented representations. This combination is more effective in some designs, such as the *Finger Shadow* or the *Bricks* which convey information on the dynamics or physicality of gestures superimposed on aeronautics system elements. One important lesson learnt is that impression-oriented representations should be able to disclose interactions, while still preserving high priority result-oriented representations. This requirememt is not observed with the *Onion*, *Blurring* and *Button Shadow* designs.

CONCLUSION

This paper presented an exploration of designs to enhance mutual awareness among airliner pilots confronted with touchscreens by supplementing touch-based gestures with graphical elements. Thanks to activity analysis, graphical design work and walkthroughs, we provide graphical dimensions and rules enabling the combination of impression-based and result-based gesture representations. Future work with this design should take into account that all the components except localization are validated, and that time and trace are to be kept but only for their subjective effect. Several graphical aspects are to be maintained: color, grain, continuity (alignment), saturation, shape (pictograms), animation. However, *Blurring* must be discarded. Further work should include assessing by crews of two airline pilots, the combination of effective touch-based gestures and representations in a more operational environment.

The broader impact of this work relates to the recent concept single pilot operation (SPO) [39] planned with the second pilot on the ground, which is the next challenge in aeronautics R&D. The SPO concept raises additional critical concerns regarding mutual awareness [41][11]. The principle of the Gesture View presented in this paper may enable this issue to be addressed.

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