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How do interactive tabletop systems influence collaboration?

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ABSTRACT

This paper examines some aspects of the usefulness of interactive tabletop systems, if and how these impact collaboration. We chose creative problem solving such as brainstorming as an application framework to test several collaborative media: the use of pen-and-paper tools, the "around-the-table" form factor, the digital tabletop interface, the attractiveness of interaction styles. Eighty subjects in total (20 groups of four members) participated in the experiments. The evaluation criteria were task performance, collaboration patterns (especially equity of contributions), and users' subjective experience. The "around-the-table" form factor, which is hypothesized to promote social comparison, increased performance and improved collaboration through an increase of equity. Moreover, the attractiveness of the tabletop device improved subjective experience and increased motivation to engage in the task. However, designing attractiveness seems a highly challenging issue, since overly attractive interfaces may distract users from the task.

1. Introduction

1.1. Goal of the research

This paper relates to characterizing the *usefulness* of interactive collaborative tabletop systems: we explore the benefits of using an interactive tabletop device in a collaboration context, whether this changes the way people work together within a group, and if so, to what extent. To this end, we review research on creative problem solving in order to design the most adequate application framework. By means of two iterative experiments we isolate the influence of several features of tabletop systems and rely on social and cognitive psychology literature to interpret our results.

2. Tabletop devices and their evaluation

Our goal is to evaluate interactive tabletop paradigm by measuring its benefits with regard to traditional collaboration situations. Tabletop systems are multi-user horizontal interfaces for interactive shared displays. They implement around-the-table interaction metaphors allowing co-located collaboration and face-to-face conversation in a social setting (Shen et al., 2006). Tabletop prototypes have been developed for various application fields such as games, photo browsing, map exploration, planning tasks, classification tasks, interactive exhibit medium for museums, drawing, etc. (Scott & Carpendale, 2006; Shen et al., 2006). An abundant literature on tabletop computing has developed in the recent few years, and contains a large number of user studies, which we classify as follows:

- *Ethnographic studies or user needs analyses*: In this category, the methodological framework relies on ecological observations and formalization of what happens when users are involved in tabletop activities. Such methods are characterized by minimal intervention on the part of the experimenter and a realistic context of observation. Results are mainly used to inform the design of future systems: they do not exactly constitute evaluations because they take place either very early in the design process (e.g. task analyses on non-augmented tables or mock-up studies, see Kruger, Carpendale, Scott, & Greenberg, 2004; Müller-Tomfelde, Wessels, & Schremmer, 2008; Scott, Carpendale, & Inkpen, 2004) or very late in the process (after field deployment of systems, see Hornecker, 2008; Mansor, De Angeli, & De Bruijn, 2008; Rick et al., 2009; Ryall, Ringel Morris, Everitt, Forlines, & Shen, 2006; Wigdor, Penn, Ryall, Esenther, & Shen, 2007).
- *Tabletop interface evaluation*: A second category of user studies aims to evaluate design concepts, implementations, or applications. There are two ways of achieving such evaluations: user tests within an iterative design process (see e.g. Cao, Wilson, Balakrishnan, Hinckley, & Hudson, 2008; Hilliges, Baur, & Butz, 2007; Jiang, Wigdor, Forlines, & Shen, 2008; Mazalek, Reynolds, & Davenport, 2007; Pinelle, Stach, & Gutwin, 2008; Rick &

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Rogers, 2008) and comparisons between several design solutions (see e.g. Block, Gutwin, Haller, Gellersen, & Billinghurst, 2008; Jun, Pinelle, Gutwin, & Subramanian, 2008; Marsfhall, Hornecker, Morris, Dalton, & Rogers, 2008; Pinelle, Barjawi, Nacenta, & Mandryk, 2009; Ringel Morris, Cassanego et al., 2006; Ringel Morris, Paepcke, Winograd, & Stamberger, 2006).

• *Tabletop paradigm evaluation*: In this last category we include studies comparing the realization of the same activity on a tabletop system and on a given control condition (*e.g.* traditional desktop systems, interactive boards, pen-and-paper, etc.). Although the two aforementioned categories (ethnographic studies and interface evaluations) enable researchers and practitioners to gain an increasingly detailed picture of user experience in tabletop interface use (e.g. effectiveness, usability, pleasantness, enjoyability of interaction, etc.), evaluating the *usefulness* of these systems remains a key issue. It can be addressed only via a comparison of a tabletop with alternate traditional tools to identify, quantify and understand its benefits and drawbacks with respect to other interaction and collaboration media. There are very few studies of this kind. For example, Rogers and Lindley (2004) reported on positive effects of a tabletop interface compared with a wall display or a computer screen in the context of a collaborative task: they observed more interactions and more role changes (visible as circulation of the input device within the group) in the tabletop condition. Such a result is highly encouraging since the authors were not able to take full advantage of all technological features available in tabletop systems today: for example Rogers and Lindley's device allowed only a single touchpoint (by means of a stylus shared by group members) and a single viewpoint (participants seated side by side, and not face to face). Rogers, Lim, Hazlewood, and Marshall (2009) later investigated several conditions of interface accessibility and tangibility by testing three collaboration devices: a shared laptop with a single mouse, a multi-user tabletop and a physical–digital setup (multi-user tabletop + RFID-enabled tagged objects). The laptop condition gave rise to more verbal contributions and larger differences in physical contribution between the participants (higher inequity). This can be explained by the fact that in the laptop condition there was only one entry point for all group members (i.e. one mouse to share) whereas in the tabletop and physical–digital conditions there were multiple entry points (all group members could interact directly with the task material).

Regarding the specific issue of collaboration around an interactive tabletop device, user studies (our second category) enable researchers to observe and describe how people collaborate with such technology, while comparative studies (our third category) enable them to understand why it is so. For example, user studies provided descriptions of collaboration patterns around the tabletop such as turn-taking and parallel collaboration (Shaer et al., 2010), role assignment strategies (Tang, Pahud, Carpendale, & Buxton, 2010), non-verbal behaviors promoting mutual awareness (Conversy et al., 2011), collaborative learning mechanisms such as suggestion process, negotiation, joint attention and awareness maintenance (Fleck et al., 2009), or subjective benefits of tabletop collaboration (Hartmann, Ringel Morris, Benko, & Wilson, 2010; Smith & Graham, 2010). To explain these benefits, comparative studies have emphasized the positive role of multiple entry points for collaboration (Marshall et al., 2008; Rogers et al., 2009): when compared to a device with a single entry point (e.g. one mouse to be shared by the group members) interactive tabletop systems improve collaboration. In the present study we wish to extend our understanding of the influence of such device on task performance, collaborative behaviors, and subjective experience of

collaborating participants. For this purpose, we chose to compare the use of an interactive tabletop device with a traditional pen-and-paper condition (which is multi-user and still constitutes a reference situation for group meetings) and explore the effects of two other important features of interactive tabletops: the form factor, which enables people to sit around the table and notably face-to-face, and the attractiveness of the device, which we believe is likely to increase users' involvement in the task. A collaborative creative problem solving task seemed particularly relevant to provide a context for these experiments, as explained below.

3. Creative problem solving as an application framework

In this section, we will show that tabletop systems – which are expected to support collaboration by providing sharing and visualization facilities while emphasizing the social nature of collaboration – appears to meet the requirements of creative problem solving. Creativity is the ability to produce work that is both novel and appropriate (Sternberg, 1998). One of the most popular creative problem solving methods is *group brainstorming*: this method enhances idea generation through cognitive stimulation (i.e. exposure to other participants' ideas, see Dugosh & Paulus, 2005; Dugosh, Paulus, Roland, & Yang, 2000; Nijstad, Stroebe, & Lodewijkx, 2002) and social comparison (i.e. the possibility to compare one's own performance to the others', see Bartis, Szymanski, & Harkins, 1988; Dugosh & Paulus, 2005; Harkins & Jackson, 1985; Michinov & Primois, 2005; Paulus & Dzindolet, 1993).

However, a major shortcoming of "oral" brainstorming is the necessity of managing *speech turns*: each participant has to wait for his turn to give an idea, and only one idea can be given within a turn. This severely interferes with idea generation process (Nijstad, Stroebe, & Lodewijkx, 2003) and results in "production blocking" (Diehl & Stroebe, 1987; Michinov & Primois, 2005). One simple solution is to use the written instead of the oral channel to record the ideas, which can be referred to as brainwriting (Isaksen, Dorval, & Treffinger, 2000; VanGundy, 2005), Brainpurge (VanGundy, 2005), etc. A shareable interactive surface is likely to bring new facilities for these activities: saving/loading the session, performing grouped treatments on items (i.e. moving all items together) and making easier the follow-up analysis (no transcription needed). Above these general benefits, a digital tabletop system can implement computer-supported rotations of items (Shen, Vernier, Forlines, & Ringel, 2004) which help to manage the orientation et re-orientation of items for people around the table.

Creativity-supporting tabletop applications have been developed previously (Hartmann et al., 2010; Hilliges et al., 2007; Streitz, Geißler, Holmer, & Konomi, 1999; Warr & O'Neill, 2006) but their actual benefits have not been measured experimentally. The study by Hilliges et al. (2007) is noteworthy since it compared a digital brainstorming application composed of an interactive table and a wall-mounted display to their pen-and-paper counterparts. The results showed no difference in task performance between the two conditions but subjective evaluations were globally favorable to the digital condition. However, since the application involved both a tabletop and a wall-mounted display in all conditions, it was not possible to distinguish the respective benefits of each device within the results.

4. Overview of the experiments

This research included two steps: for the first experiment we found it important to compare the use of an augmented multi-user tabletop system to the reference situation of creative problem solving sessions which relies on pen-and-paper tools and takes place in
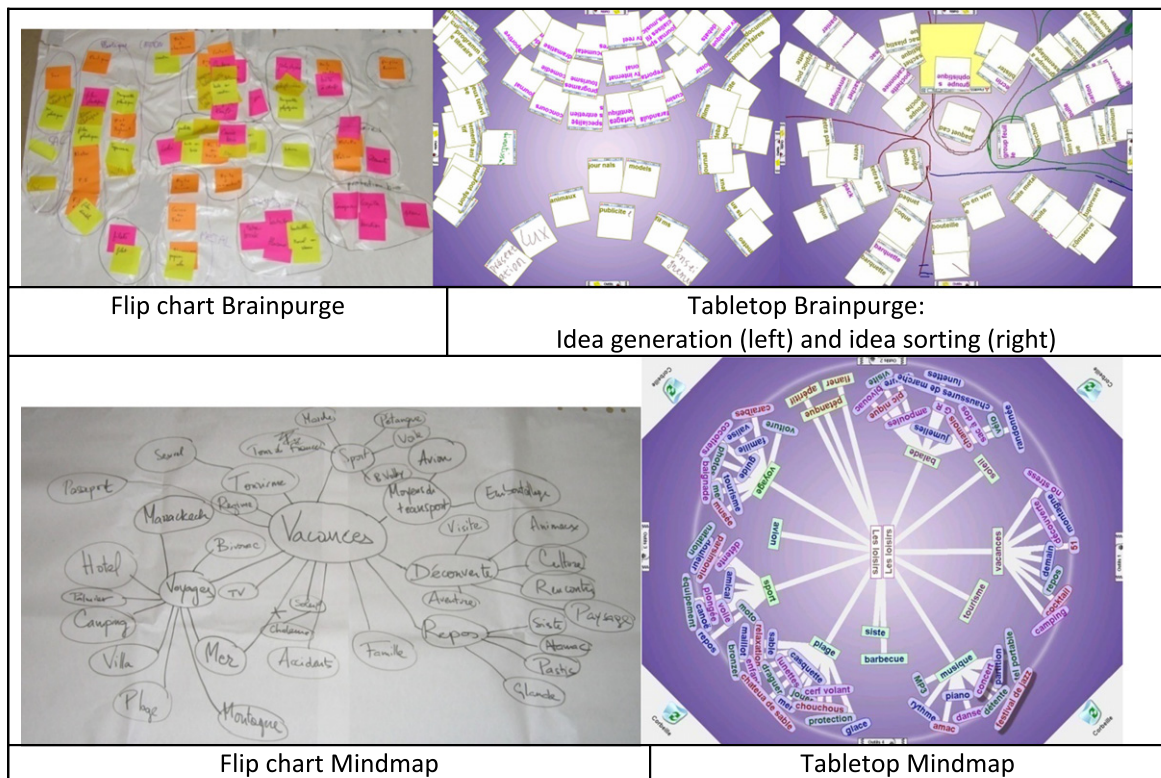
Flip chart Brainpurge	Tabletop Brainpurge: Idea generation (left) and idea sorting (right)
Flip chart Mindmap	Tabletop Mindmap

Fig. 1. The creative problem solving tools (Brainpurge and Mindmap) in the two experimental conditions (flip chart and digital tabletop).

front of a flip chart (VanGundy, 2005). The results led us to formulate hypotheses related to tabletops' form factor and to attractiveness of the device. Accordingly we designed the second experiment to complete the picture with a new control condition consisting of a pen-and-paper session around a non-augmented table and a digital tabletop condition enriched with more targeted and more attractive interaction styles. In both experiments we used a repeated-measures design in which groups of participants had the opportunity to compare the interactive tabletop condition and the control condition in similar creativity exercises.

5. Experiment 1

5.1. Participants

Twelve groups of four participants (48 users in total) were involved in this first experiment. Every group included students, teachers and/or staff members from our university. Groups composed of students only were excluded in order to avoid excessive familiarity among participants and to simulate the conditions of creative problem solving sessions in a more realistic fashion. Overall, our users were 33 students, six teachers and nine staff members, 27 men and 21 women, aged 20–53 years (mean = 27.9, SD = 7.7).

5.2. Materials

For the interactive tabletop condition, we used a 88-cm MERL DiamondTouch device (Dietz & Leigh, 2001) with a $1400 * 1050$ projected display: participants were seated around the table and interacted with finger-input on the display. The experimenter, who also played the role of session facilitator, sat aside on a highchair. In the control condition participants were all equipped with sticky notes and marker pens and were seated in front of a flip

chart with the experimenter standing beside it (i.e. the reference situation for creative problem solving sessions, see VanGundy, 2005).

We tested two creative problem solving tools in those conditions: a Brainpurge on sticky notes (VanGundy, 2005) and a Mindmap (Buzan, 1991). These two methods are based on associative logics and belong to the divergent thinking paradigm (Runco, 2004). In both cases participants were asked a general question (e.g. "What does the field of leisure make you think of?"): during the Brainpurge ideas are written down by each participant on sticky notes, then shared and collectively sorted in order to bring out categories of ideas. In the Mindmap, ideas are generated orally by the participants, written down and organized by the facilitator in the form of a tree: the initial question in the center, first-level associations as branches, second-level associations as leaves, etc. (see Buisine, Besacier, Najm, Aoussat, & Vernier, 2007 for more details). The main difference between the two methods concerns the direction of associative logics: Brainpurge explores a semantic network horizontally (within a constant level of abstraction) whereas Mindmap explores it vertically (addressing categories and subcategories). Fig. 1 illustrates these tools in our two experimental conditions.

5.3. Implementation

The digital tabletop creative applications were implemented using the DiamondSpin toolkit (Shen et al., 2004). In the tabletop Brainpurge, each user created his notes using a personal menu located on the edge of the table closest to him. The user can edit his notes (using handwriting, drawing, or typing in on a virtual keyboard), move, rotate, delete, resize, or miniaturize them. Miniaturization consists in pressing a button to instantly shrink a note down to minimal size. It also represents a (reversible) validation operation, since the note is no longer editable when shrunk down

(this enables users to manipulate notes without writing on them). The default spatial orientation of notes is different in the generation and categorization stages (see Fig. 1): in the generation stage, virtual notes cannot be moved out of each participant's personal area and their default orientation is centered on their author (i.e. on a virtual point located outside of the table); in the categorization stage, notes are movable on the whole display area and default orientation always faces the tabletop's nearest edge. The categorization stage is then launched by the experimenter. Users can write directly on the table background, for example to define the boundaries of zones located on the table surface, and label idea categories.

The tabletop Mindmaps are built top-down from the root label (this label is duplicated and the copy is rotated upside-down to be readable by all four users) by using double-tap-and-drop actions to create new nodes. All users can create or move nodes but editing these nodes must be consensual: this is why text input is allowed from a single source only (a physical wireless keyboard) which is managed by the facilitator (see Buisine et al., 2007). This constraint mimics the pen-and-paper procedure in which the facilitator is the only one who holds the marker, in charge of transcribing the participants' ideas. Nodes of the hierarchy can be freely relocated on the table, and sub-hierarchies follow their parent nodes. Node orientation is constrained: first-level nodes always face the closest outside edge of the table and second-level nodes always have their back facing their parent node. Users can also rotate the whole display to change the view without changing the arrangement of the hierarchy.

5.4. Procedure

Participants were informed that the aim of the research was to evaluate a new kind of collaborative medium, the multi-user tabletop device. The creative problem solving methods (Brainpurge or Mindmap) were explained, and Osborn's rules (1953) were delivered: Focus on quantity, Withhold criticism, Welcome unusual ideas, Combine and improve ideas. Each group carried out two short creative problem solving exercises successively: one in the pen-and-paper control condition and one in the digital tabletop condition (repeated-measures design). Counterbalancing of conditions and topic assignment (what the creative problem solving exercises were directed toward) is shown in Table 1. Assignment of groups to experimental cases was randomized. The structure of the reflection being slightly different between the two methods

Table 1

Description, for each of the 12 participant groups, of the creative problem solving tool used (Brainpurge or Mindmap), the topics addressed (industrial sectors of Packaging, Television programs, Media, and Leisure) in each condition (digital Tabletop and control Fip chart) and their order (in square brackets: half of the groups performed the Tabletop condition first, and half performed the Flip chart condition first).

Group ID	Tabletop condition	Flip chart condition
	Creative problem solving tool used: the Brainpurge	
1	Television [#1]	Packaging [#2]
2	Packaging [#1]	Television [#2]
3	Television [#1]	Packaging [#2]
4	Packaging [#2]	Television [#1]
5	Television [#2]	Packaging [#1]
6	Packaging [#2]	Television [#1]
	Creative problem solving tool used: the Mindmap	
7	Media [#1]	Leisure [#2]
8	Leisure [#1]	Media [#2]
9	Media [#1]	Leisure [#2]
10	Leisure [#2]	Media [#1]
11	Media [#2]	Leisure [#1]
12	Leisure [#2]	Media [#1]

we ran them on different kinds of questions: a creative search at the product level for the Brainpurge (on Packaging and Television programs) and another one at the sector level (on Leisure and Mass media). The typical question for starting the Brainpurge was "What kinds of packaging (respectively television programs) do you know?" and the one question in the Mindmap was "What does the field of leisure (respectively mass media) make you think of?" All exercises had to be achieved within a limited timeframe (8 min for idea generation in the Brainpurge, 10 min for idea categorization in the Brainpurge, and 10 min for the Mindmap).

The tabletop condition was preceded by a familiarization stage where the interface's functionalities were demonstrated to the participants. Both tabletop and flip chart conditions were video-recorded. At the end of the experiment, users had to fill in a questionnaire to assess several subjective variables on 7-point Likert scales. The whole experiment lasted about 1 h for each group.

5.5. Data collection

In this section, we detail the three kinds of variables that were collected.

5.5.1. Performance criteria

Evaluating creativity is a complex issue since there is no "right answer" to a creative problem. Some of the existing tests designed to assess individuals' capacity for creativity (e.g. the Torrance Test of Creative Thinking) cope with this complexity by measuring individual performance with regard to normative data (typically: a database of the most frequent answers to the same problem, see Torrance, 1966). For the particular problems we submitted to our participants (television, packaging, media, leisure), no normative data exist. Hence we decided to create our own database of answers by aggregating all groups' ideas on the same topic. Subsequently, each group's production was expressed as a percentage of this reference production, which accounts for quantity of ideas generated by each group. It must be noted that in the literature on creative problem solving, quantity is considered to be correlated to quality of the creative production (Osborn, 1953; Parnes & Meadow, 1959): the more ideas are generated, the more likely it is that good ideas arise.

This production index was the only performance metric for the Mindmap exercise. For the Brainpurge, two independent judges also carried out a meta-categorization of the aggregate of ideas in order to analyze each group's performance in the categorization stage. For this meta-categorization we adopted a card sorting procedure, a technique used in information architecture design (Nielsen, 1993). The judges had to arrange the global idea pool and generate a two-level category tree, in an unsupervised way (which means that no category labels were supplied). This ad hoc taxonomy, reached by consensus, enabled us to build a dual index (partly inspired by Nijstad et al., 2002) accounting for both the width (number of meta-categories) and depth (number of categories) of each group's outcome: each meta-category represented in a group's production was rewarded by a 10-point score, and each category by an additional 1-point score. Each group's final categorization performance was expressed as a percentage of the aggregate's meta-categorization.

5.5.2. Collaborative behaviors

We chose to assess collaboration through the quantification of contributions and the equity between participants. Indeed for tasks involving negotiation, for collaborative learning, and every time it is important for all members to have their say, equity per se is a desirable state (Marshall et al., 2008). Equity also refers to "democracy", in Habermas' sense (1984), as a set of ways to ensure the information communicated by the various participants is done

so with minimal distortion (as opposed to a repressive communicational framework). Moreover, recent studies found that equity in conversational turn-taking is correlated to the collective intelligence of the group, a factor that explains a group's performance on a wide variety of tasks (Woolley, Chabris, Pentland, Hashmi, & Malone, 2010). Hence in our experiment we decided to assess collaboration through the following inequity index I, where N = size of the group, $1/N$ = the expected proportion of events if each participant contributes equally, and O_i = the observed number of contributions for each individual.

$$I = \left| \frac{1}{N} - \frac{O_i}{\sum_{i-1}^{N} O_i} \right| \times 100$$

Similar quantification of participants' contributions can be automated by logging interface actions made by individuals (Ringel Morris, Cassanego et al., 2006; Wigdor, Jiang, Forlines, Borkin, & Shen, 2009) but we applied our inequity index to a more complete set of behavioral variables, including spoken contributions. We manually annotated spoken and gestural contributions of each participant from the video-recordings of the sessions: as speech acts, we collected assertions (e.g. giving an idea), information requests (e.g. requesting a clarification about an idea, for example "What do you mean by a shell"), action requests (e.g. asking a participant to "send a note over"), answers to questions, expression of opinions and off-task talk. We also annotated communicative gestures as another kind of contribution to the collaborative task: pointing to an item, moving a note, interrupting someone or requesting a speech turn by a gesture. In the tabletop condition, this variable also includes gesture-inputs on the table, with the exclusion of note creation/edition/suppression actions, which were not considered as communicative or collaborative gestures.

The whole corpus (174 min) was annotated by a single coder but in order to assess the reliability of annotation a second coder independently annotated a 28-min extract (which represents 16% of the corpus). Inter-judge agreement (Cronbach's alpha) amounted to 0.743.

5.5.3. Subjective data

The following variables were collected in the form of 7-point Likert scales: ease of use (1–7) of each device (flip chart and tabletop system), effectiveness (1–7) of each device, pleasantness (1–7) of each device; easiness of communication (1–7) in each condition, effectiveness of communication (1–7) in each condition, pleasantness of communication (1–7) in each condition; easiness of group work (1–7) in each condition, effectiveness of group work (1–7) in each condition and pleasantness of group work (1–7) in each condition. Furthermore, users were particularly prompted to make qualitative comments at their leisure. Likert scale results of the questionnaire were analyzed quantitatively and free comments were analyzed qualitatively.

5.6. Results

Statistical analyses were performed by means of ANOVAs using SPSS. Results with means and standard deviations are detailed in Table 2.

No significant effect of the condition (control flip chart and digital tabletop) appeared on any of our performance indices: production index for the Brainpurge, categorization index for the Brainpurge, production index for the Mindmap. Possible confounding effects produced either by the topics addressed or by the order of conditions were checked by means of t-tests. This analysis showed no significant effect of the topics in the Brainpurge ($t(5) = 1.21$, NS) or in the Mindmap ($t(5) = 0.72$, NS) and no

significant effect of the order of conditions ($t(5) = 0.86$; NS for the Brainpurge and $t(5) = -0.93$, NS for the Mindmap).

With regard to collaborative behaviors, the variables "expression of opinion" and "off-task talk" comprised too many missing values to be analyzed. Other raw data showed no significant difference in the absolute number of any of the behaviors. Analysis of the inequity index showed that participants' verbal contributions (sum of all behaviors but communicative gestures) were significantly more equitable in tabletop than in flip chart condition. Finally, the same result arose for communicative gestures: they were significantly better-balanced in the tabletop condition than in the flip chart condition.

The results of subjective data are somewhat contradictory between the Brainpurge and Mindmap exercises. For the Brainpurge, the use of pen and paper was evaluated as easier and more efficient than use of the digital tabletop. According to the comments added by users this result can be mainly attributed to the size of the table, which proved too small for four users manipulating more than a hundred notes at the same time. The other variables examined (pleasantness of use; ease, effectiveness and pleasantness of communication; ease, effectiveness and pleasantness of group work) showed no significant difference between tabletop and flip chart conditions.

For the Mindmap exercise, the tabletop was rated as significantly more pleasant to use, and allowing a more pleasant communication between participants. There was no significant effect of the condition (control flip chart or digital tabletop) on ease of use and efficiency of Mind-map building as well as for the other variables examined.

5.7. Discussion

The results of this first experiment can be summarized as follows: the digital tabletop had no influence on the creative performance, but it did improve collaboration in the sense that participants had more equitable contributions compared to the control flip chart condition. Finally, subjective evaluation showed mixed results: users preferred pen-and-paper for the Brainpurge but preferred the digital tabletop for the Mindmap.

The results on collaborative behaviors showed remarkable consistency between the two creative problem solving tools (Brainpurge and Mindmap). Physical accessibility of the device can naturally explain why gestural contributions were more equitable in the tabletop condition. However, physical accessibility does not explain why the amount of verbal contributions is constant over the conditions: on the contrary, with physical accessibility the verbal channel should have been less important to collaborate. Moreover, physical accessibility does not explain why verbal contributions were more equitable with the tabletop system. An alternative explanation can be found in the literature on the *social loafing* phenomenon (Karau & Williams, 1993; McKinlay, Procter, & Dunnett, 1999; Serva & Fuller, 1997): in a group situation, some participants tend to under-contribute (with comparison to a situation where they would work alone). Conversely, other participants tend to over-contribute, which is termed *social compensation*. The simultaneous occurrence of social loafing and social compensation results in the emergence of leaders and followers (high inequity), as we observed in the control flip chart condition. McKinlay et al. (1999) showed that a remote electronic brainstorming application decreased social compensation, resulting in more equitable contributions but also in an overall decrease of contributions (which we did not observe in our experiment). We showed that a digital tabletop system can decrease both social loafing and social compensation, leading to an overall constant amount of contributions, but a significantly better balance among group members.

Table 2
Means (*m*), standard deviations (SD), degrees of freedom (DOF), *F* values (*F*) and significance (Sig.) for the main dependent variables in the Flip chart control condition and the Digital tabletop condition.

	Flip chart control		Digital tabletop				
	m	SD	*m*	SD	DOF	*F*	Sig.
Performance							
Production index in Brainpurge (by group)	54	9.6	64	20.3	1/5	0.76	NS
Categorization index in Brainpurge (by group)	68.7	10.1	55.8	13.6	1/5	2.13	NS
Production index in Mindmap (by group)	50.8	12.2	46.5	16.4	1/5	0.92	NS
Collaboration							
Number of communicative gestures in Brainpurge (by user)	14.1	4.6	15.8	2.7	1/23	3.87	NS
Number of communicative gestures in Mindmap (by user)	4.3	4.6	6	3.3	1/23	3.59	NS
Inequity of speech acts in Brainpurge (by user)	14.9	8	10.2	7.3	1/23	7.93	*
Inequity of speech acts in Mindmap (by user)	12.1	7	10.3	9.2	1/23	7.35	*
Inequity of communicative gestures in Brainpurge (by user)	20.4	15.4	9.1	5.8	1/23	12.29	**
Inequity of communicative gestures in Mindmap (by user)	20.4	15.4	9.8	6.8	1/23	8.94	**
Subjective data							
Ease of Brainpurge	5.9	0.9	4.8	1.4	1/23	8.41	*
Efficiency of Brainpurge	5.5	0.9	5	1.1	1/23	6.27	*
Pleasantness of Mindmap	4.6	1.3	6	1.2	1/23	10.43	**
Pleasantness of communication in Mindmap	5	1.3	5.9	1.3	1/23	5.01	*
Efficiency of group work in Mindmap	5.2	1.2	5.7	1.3	1/23	3.56	NS
Pleasantness of group work in Mindmap	4.8	1.4	5.8	1.3	1/23	4.23	NS
Ease of Mindmap	5.4	1.3	5.4	1.3	1/23	<0.1	NS
Efficiency of Mindmap	5	1.3	5.4	1.3	1/23	1.02	NS

NS, Non-significant result.
* *p*-value < 0.05.
** *p*-value < 0.01.

In our view two hypotheses can account for this result:

- (H1) the decrease in social loafing can result from the spatial setup of participants around the table (in the control condition they were side-by-side, facing the flip chart). The underlying reason can be a higher group cohesiveness (which was shown to decrease social loafing, see Karau & Hart, 1998) or a stimulation of social comparison, providing indirect self-evaluation which is also known to decrease social loafing (Harkins & Szymanski, 1988).
- (H2) the attractiveness of a new technology may have motivated users to contribute to the task just for the fun of using the interactive tabletop system (external incentive to users' contributions). While H1 relies on a group effect, H2 suggests an increase in individual involvement of users, individual motivation, which can also be a moderating factor of social loafing (Brickner, Harkins, & Ostrom, 1986; Shepperd, 1993).

To decide between these two hypotheses we designed a second experiment: it seemed necessary to create a new control condition with pen-and-paper tools around a non-augmented table (to test H1) and a new tabletop condition with refined interaction styles in an attempt to further improve the attractiveness of the device (to test H2). Finally, given the lack of effect on creative performance and the mixed results on the subjective evaluations, a secondary goal of Experiment 2 was to integrate user requirements collected during Experiment 1 (as qualitative data, informal comments or our own observations) in order to improve our tabletop creative applications.

6. Experiment 2

6.1. Participants

Eight groups of four participants (32 users in total) were involved in the second experiment. 26 participants were students, two were teachers and four were staff members (all different from Experiment 1), 21 were men and 11 were women. Participants were aged 19–39 years (mean = 25.4, SD = 3.7). We followed the same rule as in Experiment 1 that excessive familiarity should be avoided in the groups and consistently recruited participants that did not know each other.

6.2. Materials

For this second experiment we used a 107-cm MERL Diamond-Touch (instead of the 88-cm model used in Experiment 1) in order to meet users' requirements for a larger tabletop surface.

The spatial setup used in Experiment 1 for the tabletop condition (the four participants around the table with the experimenter sitting nearby on a highchair) was used in both conditions for Experiment 2: with the new digital tabletop on the one hand, and with the new pen-and-paper control condition on the other hand. In the latter case, we used a 145-cm non-augmented table with a 110-cm sheet of paper set on it to stand in for the flip chart; participants were equipped with sticky notes and marker pens.

We tested only the Brainpurge tool in Experiment 2. This exercise was more challenging since in Experiment 1 users preferred the pen-and-paper condition to carry out the Brainpurge. Moreover, the other evaluation criteria (performance and collaborative behaviors) showed such consistent results over the two creative problem solving methods (Brainpurge and Mindmap) that we assumed they were not method-dependent: testing several methods did not, therefore, seem necessary.

6.3. Implementation

The new interaction styles that were implemented for the interactive tabletop Brainpurge application are described and illustrated in Appendix A. These interaction styles were designed in order to increase the device's attractiveness and test our H2 hypothesis.

6.4. Procedure

In order to get comparable results, we used in Experiment 2 (E2) the same repeated-measures procedure as in Experiment 1 (E1). However, it seemed necessary to introduce a new independent variable to the protocol because access to Google Images (see

Table 3
Description, for the eight participant groups, of the topics addressed (packaging or television programs) in each condition (advanced digital tabletop and control pen-and-paper on a table), of their order (in square brackets: half of the groups performed the paper-and-table condition first and half performed the advanced tabletop condition first) and of the availability of Google Images (symbolized by GI).

Group ID	Advanced tabletop	Paper-and-table condition
	Creative problem solving tool used: the Brainpurge	
1	Packaging [#2] GI	Television [#1]
2	Packaging [#2]	Television [#1]
3	Television [#2] GI	Packaging [#1]
4	Television [#2]	Packaging [#1]
5	Television [#1] GI	Packaging [#2]
6	Television [#1]	Packaging [#2]
7	Packaging [#1] GI	Television [#2]
8	Packaging [#1]	Television [#2]

Appendix A) seemed likely to bias our experiment. It can indeed provide additional cognitive stimulation and source of inspiration, leading to unfair advantages over the pen-and-paper condition. Therefore, only half of the groups were provided with the Google Images functionality: this enabled us to assess its impact on creative problem solving and still compare our two experimental conditions within a sub-sample. Table 3 presents the counterbalancing scheme for our new conditions: for convenience reasons, and to distinguish them from the E1 conditions, we term them "advanced tabletop" and "paper-and-table" conditions respectively. Assignment of groups to experimental cases was randomized.

The tabletop condition was preceded by a familiarization stage to demonstrate interface functionalities and let the participants manipulate them during 5 min. Both tabletop and paper-and-table conditions were video-recorded. At the end of the experiment, users had to fill in the same questionnaire as in Experiment 1. Furthermore, in order to test our H2 hypothesis, we added a few scales (fun of use, self-assessment of creativity) as well as a customized motivation scale inspired by existing scales (Chow & Law, 2005; Pelletier, Vallerand, Green-Demers, Blais, & Brière, 1996; Rubin & Hernandez, 1988; Zaharias, 2006). For the motivation scale, users had to rate their agreement on 7-point Likert scales to the following items: "I was motivated to do well" (1–7), "The results are important to me" (1–7), "I tried to do my best" (1–7), "I would like to know my performance" (1–7), "I would like to know the others' performance" (1–7), "I would like to carry on using the interactive tabletop device" (1–7). The experiment lasted about 1 h for each group.

6.5. Data collection and results

We collected the same metrics of performance as in Experiment 1 (E1): a score for idea production and another for idea categorization, for each group. However, the baseline performance was not the same for all analyses: to compare the experimental conditions within Experiment 2 (E2) we considered the aggregated productions of all eight groups for E2, whereas to compare the results of E1 and E2 we aggregated the production of the 14 Brainpurge groups and took it as a new reference. To clarify the description of the results, the four conditions are named as follows: E1-tabletop will be called "basic tabletop" and E2-tabletop "advanced tabletop"; E1-control condition will be called "flip chart" and E2-control "paper-and-table".

In E2 the paper-and-table condition yielded better scores of idea production than the advanced tabletop condition. The use of Google Images had no significant effect on idea production ($t(6) = 0.43$, NS) or categorization ($t(6) = 1.42$, NS). Table 4 details the results for the main variables in E2.

Comparing E1 and E2, the analysis revealed that idea production was better in E2 ($F(1/13) = 13.11$, $p = 0.005$). Fisher's LSD post hoc showed that the paper-and-table was better than the flip chart ($p = 0.015$); the advanced tabletop condition was better than the basic tabletop ($p = 0.045$); the flip chart was not different from the basic tabletop ($p = 0.611$) and the paper-and-table condition was not different from the advanced tabletop ($p = 0.173$). The categorization score was higher in pen-and-paper conditions ($F(1/10) = 6.06$, $p = 0.034$). Post-hoc show that advanced tabletop was not different from basic tabletop ($p = 0.154$); flip chart was better than basic tabletop ($p = 0.038$) and paper-and-table was not different from advanced tabletop ($p = 0.137$).

Collaborative behaviors in E2 were analyzed with the same procedure as in E1. The raw data showed more collaborative behaviors in paper-and-table than in advanced tabletop condition: more speech acts and communicative gestures. There also proved to be more collaborative behaviors in E2 than in E1 (total behaviors in pen-and-paper conditions $t(55) = 13.35$, $p < 0.001$; total behaviors in tabletop conditions $t(55) = 9.12$, $p < 0.001$).

Results show that the inequity index was significantly lower in the paper-and-table condition for the following behaviors: information requests, action requests, communicative gestures, total behaviors. No significant difference appeared on the other variables of E2 dataset.
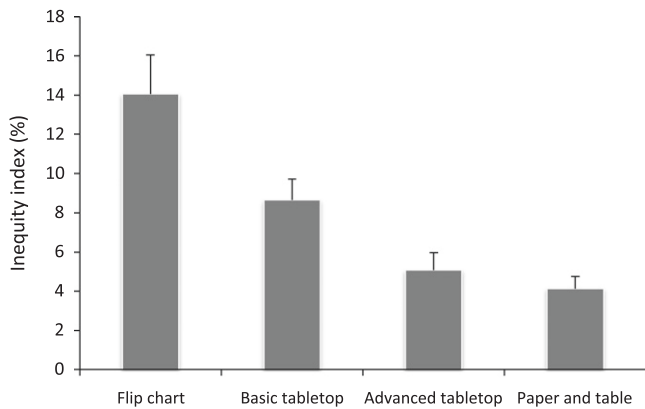
Table 4
Means (m), standard deviations (SD), degrees of freedom (DOF), F values (F) and significance (Sig.) for the main dependent variables in the paper-and-table condition and in the advanced tabletop condition.

	Paper and table		Advanced tabletop		DOF	F	Sig.
	m	SD	m	SD			
Performance							
Production index (by group)	62.5	11.7	51.6	14.3	1/7	8.11	*
Categorization index (by group)	71.1	14.3	60.2	15	1/7	4.73	NS
Collaboration							
Number of speech acts (by user)	28.2	6.8	21.5	8.8	1/31	13.41	**
Number of communicative gestures (by user)	16.9	5.8	14.3	5.6	1/31	8.99	**
Inequity of speech acts (by user)	4.7	3.8	5.2	4.8	1/31	3.05	NS
Inequity of communicative gestures (by user)	5	3.7	6.9	5.7	1/31	4.44	*
Subjective data							
Ease of use	5.8	1.3	5	1.2	1/31	7.93	**
Pleasantness of use	4.9	0.9	5.7	1	1/31	9.93	**
Pleasantness of communication	5.3	1	5.9	0.8	1/31	14.64	**
Pleasantness of group work	5.3	1.2	6.1	0.8	1/31	11.93	**
Fun	4.6	1.3	6.3	0.9	1/31	33	**
Motivation	5.2	1.1	5.7	1.1	1/31	7.76	**

NS, Non-significant result.
* p-values < 0.05.
** p-values < 0.01.

Fig. 2. Average inequity (gap between each participant's actual contribution and the theoretical value of 25%, in absolute value) in the four tested conditions: flip chart in Experiment 1, basic digital tabletop in Experiment 1, advanced digital tabletop in Experiment 2, and paper-and-table in Experiment 2.

Comparing E1 and E2, inequity proved to be significantly lower in E2 (total behaviors in pen-and-paper conditions $t(55) = 5.33$, $p < 0.001$; total behaviors in tabletop conditions $t(55) = 2.59$, $p = 0.012$). Fig. 2 represents the inequity index on the total of collaborative behaviors in the four conditions (flip chart, basic tabletop, advanced tabletop, paper-and-table).

Finally, regarding subjective evaluations, the advanced tabletop condition was better rated than paper-and-table for the following variables: pleasantness of interaction, pleasantness of communication, pleasantness of group work, fun, and motivation. The average score of willingness to carry on using the tabletop system amounts to 6/7 (SD = 0.9). However, paper-and-table was judged easier than the advanced tabletop condition. The other subjective variables examined showed no significant difference between the two conditions, and we did not compare subjective evaluations of E1 and E2 because we considered them as relative and not absolute data.

6.6. Discussion

Regarding creative performance, our results show that idea generation increased with the advanced prototype and the new control condition. The performance was notably higher in the paper-and-table condition compared with the flip chart condition, which suggests that H1 hypothesis is verified (i.e. a positive effect of the "around-the-table" setup).

Why would the around-the-table setup be beneficial? We know that brainstorming performance increases with cognitive stimulation (Dugosh & Paulus, 2005; Dugosh et al., 2000; Nijstad et al., 2002) or with social comparison (Bartis et al., 1988; Dugosh & Paulus, 2005; Harkins & Jackson, 1985; Michinov & Primois, 2005; Paulus & Dzindolet, 1993). In the first experiment, we used two kinds of creative problem solving methods, namely the Brainpurge and MindMap. Basically, mindmapping is highly prone to cognitive stimulation, because ideas are delivered verbally to all the participants. On the contrary, mindmapping is not prone to social comparison, since all actions are funneled through the facilitator, so one's ability to assess one's own contribution is low compared to the Brainpurge method, where post-it notes are written in different handwritings. The fact that our results were very similar between these two conditions did not enable us to conclude on the underlying reason explaining the benefits of the around-the-table setup. The increase in performance in the advanced tabletop condition, compared to basic tabletop, enables us to elaborate further on this issue. There are several differences between the two tabletop

conditions: some improvements in the prototype (robustness, surface size) and new styles of interaction (H2 hypothesis). However, the higher performance in paper-and-table with comparison to advanced tabletop invalidates H2. Furthermore, paper-and-table was supposed to generate low cognitive stimulation (participants did not see the content of other participants' sticky notes during idea generation) and more social comparison (they physically saw the number of sticky notes filled in and piled up by others). On the contrary the advanced tabletop condition may have led to more cognitive stimulation (participants saw other participants' notes during their creation, as well as the illustrations, which are even easier to process upside down than text) but lower social comparison (once notes were created they could be inserted into the slot and there was no feedback on the number of notes created by each participant). Therefore we assume that the primary reason for performance increase in the paper-and-table condition was social comparison, which was enhanced by the spatial configuration of participants around the table.

In Experiment 1, the lack of effect of basic tabletop on performance compared to flip chart could be explained by weaknesses in the first prototype. Besides, inferiority of advanced tabletop compared to paper-and-table might result from the absence of feedback on the other participants' performance (i.e. number of ideas generated), which limited social comparison. Another hypothesis is derived from our own observations of the sessions: in advanced tabletop, users spent more time editing notes than in paper-and-table. Text input was slower with the virtual keyboard than with marker pens, and some users lost some time searching for images (e.g. some of them happened to rephrase their notes to refine their Google search when they found the images were not satisfactory). However this hypothesis is questioned by the absence of significant difference between the sessions with and without Google Images.

Idea categorization was also improved in Experiment 2 compared to Experiment 1. Further theoretical hypotheses would be needed to interpret these results, but the improvement observed between flip chart and paper-and-table may also be linked to the spatial arrangement of participants (H1).

Overall results show that Experiment 2 yielded more collaborative behaviors and lower social loafing than Experiment 1. Conclusions that can be made about collaborative behavior are similar to those made regarding performance criteria. Improved collaboration in paper-and-table compared with flip chart can be explained by the around-the-table setup (H1). Improved collaboration in advanced tabletop compared with the basic tabletop condition may result from improvements in the prototype: indeed the H2 hypothesis (i.e. a positive impact of tabletop's attractiveness) is invalidated by the superiority of paper-and-table over the advanced tabletop condition. To explain this, one could point out that the interaction styles used in the advanced prototype may have been likely to reinforce individual manipulation behaviors more than collaborative behaviors dedicated to task completion.

Finally, subjective evaluations were globally in favor of the advanced tabletop condition. Contrary to Experiment 1, users preferred the tabletop Brainpurge to the pen-and-paper Brainpurge, especially because of the pleasant and fun nature of the interface. Our results also confirm that motivation significantly increased thanks to the advanced tabletop system. These results can be attributed to the attractiveness of the device (H2 hypothesis), because they are not attributable to a higher effectiveness (objectively or in subjective evaluations), nor to a higher ease of use (on the contrary paper-and-table was rated as easier), nor to the spatial configuration of participants (which was the same as in paper-and-table).

Table A1
Description of the interaction styles of our new Brainpurge tabletop prototype.
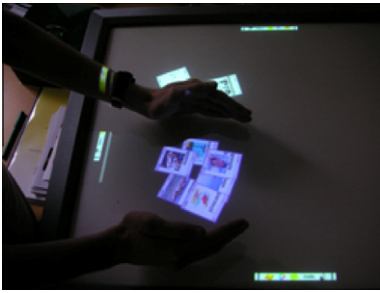
Notes grouping/de-grouping
Our first prototype did not provide any means to group the virtual notes and manipulate a pile as a single item. This proved to be an important need for the categorization phase. In our second prototype users can encircle several independent notes with both hands to group them. After a 3-s feedback confirming which notes will be grouped, the notes inside the hands cluster together and become a single object, colored in purple. Users can double-tap on the group to de-group them.
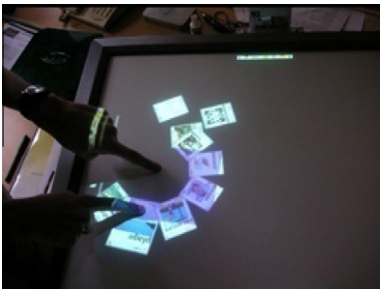

Fisheye fan and note extraction
A two-finger gesture enables users to visualize the notes belonging to a group: the first finger defines the center of a fan, while the other one defines the focus of a scroll fisheye (*i.e.* the note closest to this finger is displayed bigger). From this position the user can also extract the focused note by dragging it out of the fan while the other notes remain grouped together. Finally when the gesture is released the group of notes takes its initial clustered arrangement back.
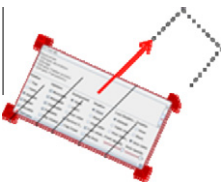

Inertia throwing
To move a note or a group of notes without moving the finger as far as their intended destination, users can throw them away. A coefficient of friction determines the speed of the moving item. Items do not collide between one another but can bounce on the table borders. Acceleration and deceleration coefficients were parameterized empirically so that an item can be thrown to the opposite end of the tabletop but cannot bounce back as far as its initial location.
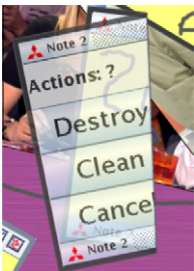
Note peeling and use of reverse side
In order to save space on notes, we implemented the possibility for users to access note-specific buttons on their reverse side by peeling the notes over, and introduced specific animations (Besacier, Rey, Najm, Buisine, & Vernier, 2007).
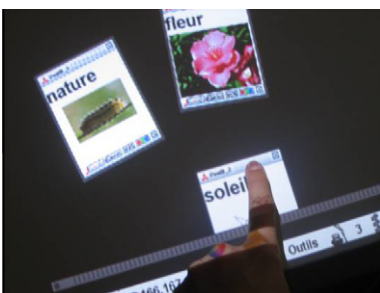
Storage and anonymity slots
In the idea generation stage, hundreds of notes accumulate and space management on the tabletop can become difficult. Besides, some users' shyness can lead them to self-censorship. We introduced virtual slots to cover these two needs: a slot is available in front of each user to slip notes into, when space is needed or when the user wants to hide a note he created. Notes are sent in a collective virtual storage space and re-appear all together during the categorization stage. In order to avoid unintentional slotting, we empirically parameterized the kinematic so that gestures that were too rapid moved the note over, not inside, the slot (Besacier et al., 2007).

Google Images search
In Experiment 1 most users were uncomfortable with handwriting or finger drawing and mainly used the virtual keyboard to edit notes. In the new prototype we provided users the 20 first results of a Google Images search with the text in the note. Users can select the image they want to insert in their notes from a pie menu.

7. Conclusion

Our two experimental iterations enabled us to better understand the potential of interactive tabletop devices for collaboration. Previous research had emphasized their multi-user nature and demonstrated their benefits with comparison to the collective use of a single-user interactive device. We chose a more challenging issue in comparing an interactive tabletop device with pen-and-paper tools, which are still great tools for collaboration. This study enabled us to identify and characterize the impact of two features of tabletop devices.

Firstly, the spatial configuration of sitting around a table appears to influence the way people work together: it is likely to improve performance and collaboration (increase of collaborative behaviors and decrease of social loafing). These effects may be a consequence of an increase in social comparison in this configuration: closer proximity and more opportunities for subtle communication channels (e.g. eye contact, facial expressions or body language). In terms of design perspectives, it would be interesting to further emphasize social comparison by means of interaction artifacts (e.g. real-time explicit feedback on each one's performance).

The second feature we identified is the attractiveness of the device, which is likely to improve subjective experience and to increase users' motivation. However, our results also suggest that highly attractive interfaces could lead to a decrease in collaboration (individuals focus on the system rather than on their partners). Combining the benefits of device attractiveness and collaboration may be achieved by explicitly designing interaction styles for collaboration, which was not the case in our study.

Several limitations of this study draw avenues for future research. First, we used ad hoc groups composed of students and university staff. Future research should extend our findings using groups of co-workers such as design teams, or ad hoc creative problem solving groups with real expectations regarding the outcome of the session. Such populations will not necessarily be subject to social loafing or to the effects of interface attractiveness in the same way as our users were. A second major shortcoming of our study is its timeframe. Longitudinal research should investigate whether our results endure over longer periods of time: When the novelty effect disappears, will the attractiveness of the device persist? Does the process of social loafing evolve with the history of the group? Finally, future research should examine other tasks to complete our understanding of interactive tabletop systems' impact on collaboration. Research addressing group performance more generally should consider interactive collaborative tabletop devices since equity in contribution was shown to correlate to the collective intelligence factor (Woolley et al., 2010). Despite the limitations of our study, we believe that it provided new knowledge on tabletop systems, on the influence of their form factor (improvement of performance and collaboration) and of their attractiveness (improvement of subjective experience and motivation). But the actual success of this new kind of collaborative medium might partly rely on solving the paradox of designing attractive interactions without diverting users from their task. The increasing interest in tabletop systems suggests that continued research is timely and warranted.

Acknowledgments

Appendix A

See Table A1.

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