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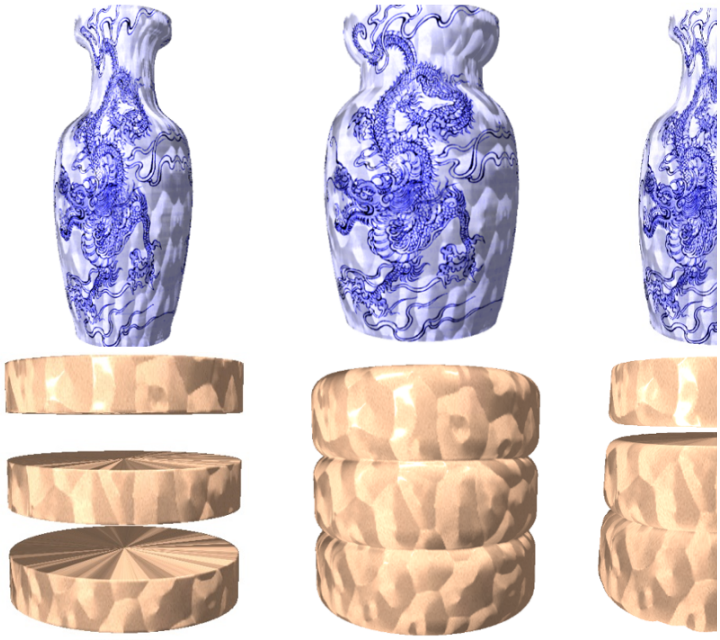

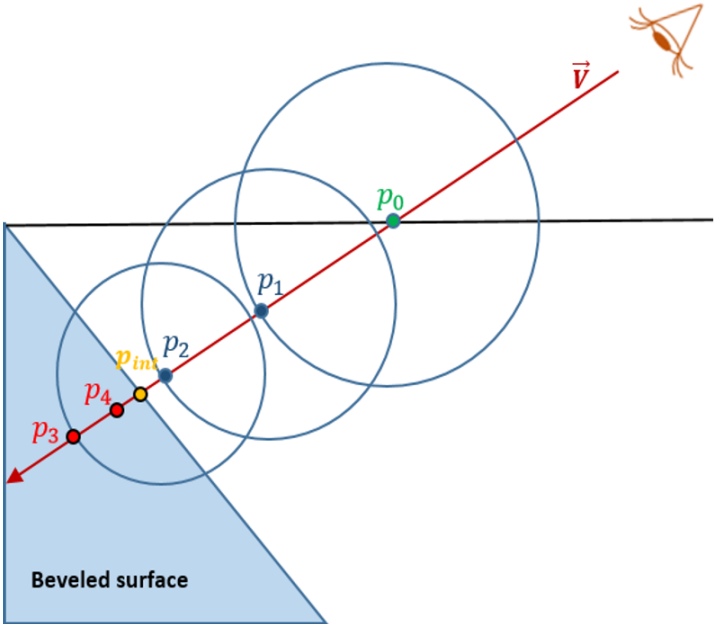

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An analysis of targeted properties of materials used for preservation and storage of heritage collections

ABSTRACT

The aim of this study was to stress the importance of investigating the properties of preservation enclosure materials in order to identify the ones that are able to protect their contents more efficiently. Since not all information on materials is covered by international standards and technical specifications, nine paper-based materials used for making preservation enclosures (file folders, passepartouts, boxes etc.) were investigated. A selective analysis of the materials' properties was carried out to determine smoothness, water absorptiveness, water wettability, water vapor permeability, tensile strength, folding endurance, bursting strength, puncture strength, as well as loss of bursting strength caused by dry heat and 100% RH. Results obtained from measuring smoothness, water absorptiveness, water wettability and water vapor transmission rate indicate that a material outside of ISO 16245:2009 grammage requirements for making file covers can exhibit more desirable properties than the one that meets multiple standards for storage and preservation. Additionally, results showed that bursting strength of enclosure materials was significantly affected by both extreme microclimate conditions. However, 100% RH had affected bursting strength of the investigated materials more than dry heat. The presented procedure proved to be a useful indicator of materials' properties within the context of heritage collections preservation and storage.

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Introduction

Library, archival and museum heritage collections consist of items made of materials such as leather, parchment, wood, metals, textiles, paper-based materials, waxes, inks and colorants, which are vulnerable to various external factors. Damage to and deterioration of these materials can occur due to exposure to inappropriate temperature and relative humidity (RH), light, UV radiation, dust particles, airborne pollutants, pests or poor handling. One of the methods to reduce or limit the effect of those factors is based on using preservation enclosures during storage, circulation, exhibitions and transport. In the Library Materials Preservation Manual (1983), enclosure is described as an envelope or a container providing protection for an item (Balloffet and Hille, 2005). Depending on their service life, enclosures can be divided into two types: temporary and permanent. Additionally, based on their contact with an item, enclosures can either be primary or secondary.

Some of the most important features of preservation enclosures are their functionality, appearance and the materials they are made of. Preservation enclosures are mainly made of paper-based materials, but may contain polyester films, bookcloth or twill tape in order to provide appropriate protection for an item. Previous studies have provided an insight into protective performance

of both historical and new preservation boxes in case of water damage and fluctuating RH (Schönbohm et al., 2010; Singer, 2010). However, few studies have focused on the properties of materials used for making custom preservation enclosures (Velensek et al., 2014). Although the characteristics of enclosure materials are described by international standards and provided by manufacturer specifications, previous studies have indicated that the existing standards are insufficient and do not guarantee paper quality (Havermans, 1995; Havermans, 2002). Furthermore, although it is well known that the quality of enclosure materials should meet the highest standards of preservation practice, our understanding of their required properties is limited. Basic requirements for preservation enclosure materials include chemical stability, smoothness, water resistance, mechanical resistance and barrier resistance. Enclosures are also expected to be space-saving and weight minimizing in nature. Enclosure materials should either be pH neutral or alkaline-buffered, depending on the type of item they are intended to preserve and the purpose of use. Alkaline-buffered paper can adsorb volatile acidic compounds more successfully than neutral paper (Meyer et al., 2014), but the long-term consequences of the process are still unclear (Meyer and Volland, 2017). Alkaline paper will also remain acid-free for a longer period of time. However, alkaline materials can be degradative for certain works of art on paper (Kolar, 1997; Meyer and Volland, 2017) and contemporary colour materials (The Library of Congress, n.d.).

This study was designed to establish a procedure for evaluation of enclosure materials, which will ultimately help identify the materials with most desirable properties. We also aimed to review targeted properties of different paper-based enclosure materials in order to gain insight into their protective performance under various threats. Enclosure materials were investigated selectively, based on their specific purpose of use. We investigated smoothness, water resistance, mechanical resistance and water vapor permeability of the materials, as well as characteristics related to their targeted properties.

Experimental

Materials

Nine commercial paper-based materials used for making both short- and long-term custom preservation enclosures were included in this study. The descriptive characteristics of the materials are given in Table 1. Applications

Table 1

The descriptive characteristics of the investigated materials

Code Name	Name and description	Grammage (g/m²)	Manufacturer
ING	Ingres paper, white	90±3%	Fabriano / Fedrigoni Group
VERG	Vergé paper, natural white, ribbed surface	100	Hahnemühle FineArt GmbH
ELF	Elephant hide paper, chamois	110	Zanders Mill / Reflex GmbH & Co. KG
NETT	Nettuno board, perla	280±5%	Fedrigoni Group
PASS	Mounting board, natural white	400	Hahnemühle FineArt GmbH
SLJ 1	Grey board, pasted extra smooth	1000±5%	Reno de Medici Group, OVARO S.p.A.
SLJ 2	Grey board, pasted extra smooth	1555±5%	Reno de Medici Group, OVARO S.p.A.
MK 1	Museumkarton, crème	800	Royal Moorman Karton
MK 2	Museumkarton, ivory	1200	Royal Moorman Karton

Table 2

Applications and quality characteristics of investigated materials

Code Name	Applications of the materials / Type of encasement	Quality standards and ecological features
ING	sleeve, wrapper, interleaving	ISO 2470 (R457), TAPPI 502-98, ISO 9706:1994, FSC recycled, Elemental chlorine-free, CE 94/62
VERG	sleeve, file cover, wrapper, interleaving	DIN 6738:2007-03, ANSI/NISO Z39.48-1992, ISO 9706:1994, ISO 16245:2009, Standard-PAT, Color-PAT
ELF	covering paper for boxes, portfolios and slipcases	FSC-STD-40-004, ASI-ACC-016
NETT	envelope, three-sided folder, phase box	ISO 2470 (R457), TAPPI 502-98, ISO 9706:1994, FSC recycled, Elemental chlorine-free, CE 94/62
PASS	frame, three-sided folder, microfilm reel identification tag	DIN 6738:2007-03, ANSI/NISO Z39.48-1992, ISO 9706:1994, ISO 16245:2009, Standard-PAT, Color-PAT
SLJ 1	portfolio	ISO 2470-1:2016, ISO 287:2017, FSC recycled
SLJ 2	box, portfolio, slipcase	ISO 2470-1:2016, ISO 287:2017, FSC recycled
MK 1	portfolio, passepartout	6738:2007-03, ANSI/NISO Z39.48-1992, ISO 9706:1994
MK 2	slipcase, box, passepartout	6738:2007-03, ANSI/NISO Z39.48-1992, ISO 9706:1994

of the materials, as well as relevant standard compliances and ecological features provided by the manufacturer are shown in Table 2.

Characterization methods

Characterization of the materials included determining the thickness and moisture content of the samples. Thickness of five materials was measured by an Enrico Toniolo DGTB01 digital micrometer, while moisture content of the nine materials was determined using an O'Haus MB 45 moisture analyser at 105°C.

Smoothness

Preservation enclosure materials should be free of topographic features and very smooth, in order to repel dust (International Organization for Standardization, 1998) and prevent mechanical damage to surrounding items. The common devices for determining topographic features of a paper surface include air leak testers, optical contact testers, surface profilers and numerous ink and liquid application tools (Singh, 2008). One of the three most common air leakage methods is the Bekk method, which presents the time interval required for vacuum pressure to drop from 50.7 kPa to 48.0 kPa (Petric Maretić et al., 2018).

In this study, Bekk smoothness of only five materials was determined, as the method is not recommended for materials with thickness over 0.5 mm or very permeable materials (International Organization for Standardization, 1995).

Water Resistance

Water outbreaks are a common threat to heritage collections. They can occur as a result of a technical failure, an accident, a human error or during natural disasters. The extent of damage caused by water can vary, as penetration is affected by factors such as porous structure, contact angle, wetting time, fibre swelling and diffusion (Sönmez and Özden, 2018).

To investigate water resistance of the materials, two types of tests were employed: the water absorptiveness and the water wettability test. Both of the properties tested describe the paper's reaction to water deposited on a specific area of paper within a defined time and are highly undesirable in enclosure materials.

Measurements of water absorptiveness were conducted with a FRANK water absorption apparatus, as described in ISO 535:2014 (E). Testing times were adjusted to both Cobb60 (paper) and Cobb120 (boards), according to the rate of the water absorption of the materials. Water absorptiveness was calculated using (1).

$$A = (m_2 - m_1)\, F \quad (1)$$

where A- water absorptiveness (g/m²), m_1 - dry mass of the sample in grams, m_2 - wet mass of the sample in grams, F = 10000 / 100 cm² (test area)

Water wettability

The water contact angle describes the interaction of water with a solid surface (Huhtamäki et al., 2018) and depends on surface geometry, roughness, contamination and deformation (Marmur et al., 2017). Maximum wetting occurs with the angle of 0°. For contact angles below 90°, materials are considered hydrophilic, while for values above 90°, they are classified as hydrophobic. For values over 150° they are considered superhydrophobic (Vuckovac et al., 2019).

The measurements of contact angle were carried out with a DataPhysics' OCA 30 device. Distilled water was used as a test liquid and drop volume was set to 1 µl. The sessile drop method was utilized. Contact angle measurements were conducted 0.5 s after the initial water-substrate contact, using Young-Laplace fitting.

Water vapor barrier resistance

Efficiency of preservation enclosures is determined by their ability to act as a barrier. The most important barrier properties include resistance to water vapor, air, odour, gases, grease or oil, but this can vary depending on the area of use (Sönmez and Özden, 2018). Water vapor permeability of the materials was investigated due to its relationship with water outbreaks.

Water vapor transmission rate (WVTR) of the materials was determined using the Cup method principle (Labthink, 2016). The apparatus consisted of a test dish with an open mouth measuring 35 mm in diameter. The dish was filled with distilled water, sealed with a lid holding a sample and placed in a desiccator containing silica gel for water vapor absorption. The test was conducted at 22±1°C and 50±2 %. Weightings of the test dish were repeated after 24 and 48 hours. WVTR was calculated using (2):

$$WVTR = \Delta m / \Delta t\, A \quad (2)$$

where Δm – sample weight change (g), Δt – time between weighing (day), A – test sample area (m^2)

Mechanical Resistance

Accidental mechanical damage to an item can happen during transport and manipulation or as a result of an earthquake. Therefore, good mechanical resistance is considered a desirable property of enclosure materials.

In this experiment, four types of strength properties were evaluated: tensile strength, folding endurance, puncture strength and bursting strength.

Folding endurance measurements were conducted using a FRANK device (Schopper type), model 840 (1974) with a tension spring range between 1 and 1.3 kp. This device is suitable for paper with thickness up to 0,25 mm (International Organization for Standardization, 1993). However, all three materials that usually get folded during use were tested, regardless of their suitability. Folding endurance (F) was calculated using (3):

$$F = \log_{10} d \quad (3)$$

where F- folding endurance, d- number of folds

A FRANK device, type 800 (1973.), with a vertical force measurement system and a maximum load of 30 kp was used in tensile force measurement. Tensile strength (T) was calculated using (4):

$$T = F/w \quad (4)$$

where F – the tensile force (N), w – the strip width (mm)

Due to grammage differences of the materials (Luo, 2019), a tensile index (TI) was calculated using (5) to facilitate comparison.

$$TI=(T/R)1000 \quad (5)$$

where TI – the tensile index (Nm/g), T – the tensile strength (kN/m), R – grammage (g/m²)

Robust enclosures made of boards are expected to provide a higher degree of protection for an item, so all types of boards (NETT, PASS, SLJ1, SLJ2, MK1, MK2) were tested for bursting and puncture strength.

Puncture strength was determined by a Frank PTI puncture tester, type 53809, in compliance with the ISO 3036 standard, while a Lorentzen & Wettre Bursting Strength Tester SE 181 was used in bursting strength measurements, in compliance with the ISO 2759 standard.

Burst index (BI) was calculated using (6):

$$BI = BS/R \quad (6)$$

where BS- bursting strength (kPa), R- grammage (g/m²)

Samples preparation

Prior to testing, all samples were conditioned for 24h at 23±2 °C and 50±5 % RH, as specified in ISO 187. To determine change in the bursting strength of the materials exposed to extreme microclimate conditions (high RH and high temperature), two additional sets of samples were prepared. Samples from the first set were placed in a desiccator and exposed to RH level of 100% at 23±2 °C for 48 hours. Samples from the second set were dried out at the temperature of 105 °C in the moisture analyser.

Results and Discussion

The measurements were repeated at least 5 times, and tables and figures in this section report average values and standard deviations where applicable.

Table 3 shows the thickness and moisture content of the investigated materials. It was observed that the moisture content is not dependant on the thickness of the material, although both properties affect the material's behaviour and end-use performance (Li, Ramaswamy and Bjegovic, 2003).

Table 3

Characterization of the materials in terms of thickness and moisture content

Code Name	Thickness (mm) ISO 534	Moisture content (%)
ING	0.14	5.13
VERG	0.16	5.49
ELF	0.13	5.57
NETT	0.39	5.39
PASS	0.63	5.82
SLJ 1	1.4*	6.47
SLJ 2	2.4*	6.21
MK 1	1.1*	5.37
MK 2	1.6*	5.59

** Values provided by the manufacturer*

Smoothness, water absorptiveness and contact angle

As material's surface properties usually differ on each side, some tests were conducted on both the wire (W) and the felt (F) side of the samples. The results of the materials' smoothness, water absorptiveness and contact angle are shown in Table 4.

As it mentioned before, the Bekk method is not recommended for materials with thickness over 0.5 mm, so SLJs and MKs have not been tested. Although the values of smoothness ranged widely, we noticed that materials used for similar purposes (e.g. ING and VERG or NETT and PASS) show similar smoothness values. The F-side of all five materials proved to have the highest levels of smoothness. This is a desirable property since the F-side of the material is frequently facing the object in need of protection. The largest difference in smoothness values of W- and F- side was observed in VERG, which can be attributed to the ribbed finish surface on the W-side.

Table 4

Smoothness, water absorptiveness and contact angle with water on each side of the materials

Code name	Sample side	Smoothness (s)	Water absorptiveness (g/m²)	Contact angle (°)
ING	W	42.98±1.0	21.28±0.89*	114.25±3.98
	F	46.04±2.37	22.67±0.71*	114.79±2.70
VERG	W	20.68±1.12	25.77±0.87*	95.62±3.24
	F	47.18±0.83	23.66±0.55*	98.78±4.92
ELF	W	240.83±13.66	13.62±0.65*	68.62±2.73
	F	255.66±13.66	14.58±0.54*	85.14±7.57
NETT	W	13.64±1.22	36.50±0.49**	114.37±4.44
	F	14.48±1.49	35.65±0.68**	114.49±2.47
PASS	W	10.92±0.89	31.25±0.97**	121.58±0.86
	F	17.94±0.74	28.38±1.08**	124.72±6.54
SLJ 1	W	n/a	415.3±8.69**	86.37±4.85
	F	n/a	423.24±6.10**	110.03±4.76
SLJ 2	W	n/a	n/a	113.65±2.88
	F	n/a	n/a	116.05±1.85
MK 1	W	n/a	n/a	116.13±3.42
	F	n/a	n/a	119.92±0.51
MK 2	W	n/a	32.56±0.26**	113.05±2.84
	F	n/a	33.69±0.21**	116.06±3.59

Cobb60 - testing time of 60 s,Cobb120 - testing time of 120 s*

Compared to other investigated materials, ELF shows the highest levels of smoothness (from 6 to over 20 times). A significant difference in results between ELF and other four materials (ING, VERG, NETT, PASS) could be attributed to the fact that glossy paper is more topographically uniform compared to the matte one (Quintana, Gómez and Villar, 2012).

By testing water absorptiveness and water wettability, we aimed to determine water resistance of the materials. Water absorptiveness was investigated according to the water uptake rate of the materials, where paper (ING, VERG, ELF) was tested for 60 s, while the boards (NETT, PASS, MK 2, SLJ 1) were tested for 120 s. Two materials (SLJ 2, MK 1) were excluded from the water absorptiveness test, since another material from the same manufacturer (SLJ 1, MK 2) was more suitable for comparison purposes in terms of grammage.

The results (Table 4) obtained from paper show no distinctive difference in water absorptiveness between the W- and the F- side. Results for ING and VERG are similar, while ELF shows the lowest water absorptiveness in the group, which can be attributed to its more compact surface.

Cobb120 results show that the values of SLJ 1 significantly differ compared to those of the other three boards (over 10 times higher water absorptiveness). Although SLJ 1 is described by the manufacturer as a smooth board, it seems to have a more porous surface than other investigated materials, as it enables a much faster water uptake.

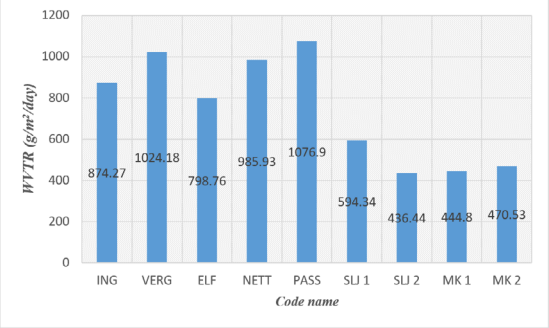
The results of contact angle measurements confirmed that most materials (with an exception of ELF) show hydrophobic behaviour (Table 4). Compared to the values of water absorptiveness, the contact angle values show a higher standard deviation. As the measuring area of the water absorptiveness occupies 112.8 mm ± 0.2 mm and the water droplet in the contact angle test takes up less than 1 mm², this could be attributed to inhomogeneous surface of the materials.

The water absorptiveness and contact angle values suggest that most often low water wettability indicates low water absorptiveness. In two materials (ELF, SLJ 1) no such relationship had been noted, which can be attributed to the compact surface of ELF and the porous structure of SLJ 1, in which the inner structure of the material plays an important role in water uptake.

Water vapor transmission rate (WVTR)

The WVTR values confirmed that water vapor barrier resistance is not exclusively dependant on grammage. We observed that lower levels of smoothness could indicate higher WVTR (Table 4, Figure 1). However, since four heavier boards (SLJs, MKs) were not applicable for smoothness measurements, general conclusions could not be drawn.

We observed that four thicker boards (MKs, SLJs) show very low WVTR (Figure 1), which could be attributed to their multiple layer structure. The data also suggest that MK 2 shows both lower WVTR and water absorptiveness than SLJ 1, although both are similar in thickness.



» **Figure 1:** *Water vapor transmission rate (g/m²/day) of the materials*

The highest levels of WVTR were obtained from PASS, which also displays low levels of smoothness and water absorptiveness, as well as the lowest water wettability of all materials used in the tests.

Folding endurance and tensile strength

Thinner materials (ING, VERG, NETT) were tested for folding endurance and tensile strength in order to determine their behaviour under tension conditions. The measurements excluded ELF (usually used as a covering paper for a board) as it rarely experiences tension conditions. However, NETT was included in the test despite exceeding thickness of up to 0.25 mm recommended by the standard (International Organization for Standardization, 1993) as it experiences both folding and tensile stress during shelf life. Number of folds and tensile force of the materials were obtained both crosswise and lengthwise. Since the test values are normally higher lengthwise than crosswise, the tensile index and folding endurance were calculated to observe strength properties of the materials in each direction, regardless of the grammage.

Folding endurance of NETT (the material used for making phase boxes) was evaluated according to the requirement that a box should be able to open and close at least 300 times (International Organization for Standardization, 2009). The results (Table 5) showed that NETT withstands over 300 foldings in both fibre directions.

Table 5

Tensile stretch, tensile index and folding endurance of three materials in both fibre directions

Code name	Fibre orientation	Tensile stretch (mm)	Tensile index (Nm/g)	Folding endurance (F)
ING	CD	4.42±0.52	39.38	2.42
	MD	1.02±0.08	46.06	2.57
VERG	CD	2.85±0.85	22.56	2.28
	MD	1.15±0.3	44.31	2.74
NETT	CD	5.24±0.43	38.54	2.48
	MD	1.82±0.28	64.93	2.94

Although the results of folding endurance for each sample varied widely, the tensile strength measurements suggest that both tensile stretch and tensile index could roughly predict folding endurance in each direction. The strong influence of tensile strength on folding endurance was also mentioned by previous studies (Williams and Krasow, 1973).

The results of both folding endurance and tensile index of ING show that the difference between the values crosswise and lengthwise is significantly lower than in the other two materials, which could be attributed to better strength, inter-fibre bonding and arrangement of the fibres (Caulfield and Gunderson, 1988; Karlovits and Gregor-Svetec, 2012). Compared to the other two materials (VERG, NETT), ING also shows the highest tensile index crosswise and the lowest tensile stretch lengthwise (Table 5).

Puncture and bursting strength

The boards were tested for puncture and bursting strength, as they preserve both heritage items and other, more fragile enclosures (file folders, sleeves) and are expected to protect their contents more efficiently.

The data shown in Table 6 suggest that both puncture and bursting strength generally increase with thickness and grammage of the material. However, we observed that in materials with a multiple layer structure (SLJs, MKs), puncture and bursting strength values are not dependant on grammage and thickness, but may be affected by the uniformity and compactness of the layers. The highest values of burst index were found in NETT, which also exhibits good tensile strength and folding endurance. Compared to grey boards (SLJs), museum boards (MKs) show higher resistance to puncture and bursting stress.

Table 6

Puncture strength and bursting strength of the materials after an exposure to dry heat* and high RH**

Code name	Puncture strength (J)	Bursting strength ISO 187 (kPa)	Bursting strength* (kPa)	Bursting strength** (kPa)
NETT	2.07±0.04	603.3±22.2	455.6±25.38	466±13.14
PASS	2.5±0	595.4±36.3	493.8±41.02	n/a
SLJ 1	4.99±0.03	1306±45.9	1073.8±63.91	972.8±38.81
SLJ 2	8.95±0.09	1837.1±71.9	1457.2±69.34	1313±64.68
MK 1	5.45±0.41	1536.89±67.1	1188±122.56	888.6±52.88
MK 2	8.44±0.21	2540.8±96.1	1872.6±99.31	1713.4±90.29

**bursting strength of the materials subjected to dry heat,*
***bursting strength of the materials subjected to high RH*

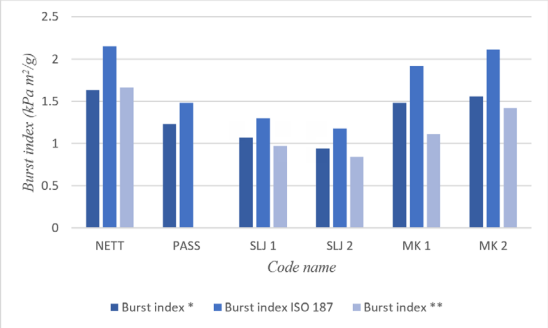
Bursting strength of materials under extreme microclimate conditions

Hygroscopic materials such as paper react to changes in RH by absorbing moisture from the environment in order to reach concentration equilibrium. To investigate how changes in moisture content affect strength properties of the materials, we designed two tests in which the samples were tested for bursting strength after being subjected to dry heat and high RH.

The results of the bursting strength measurements (Table 6) show that materials react to both dry heat and high RH with a decrease in bursting strength. However, high RH proved to have a more significant effect on the bursting strength of most materials than dry heat (with exception of NETT).

The bursting strength of PASS subjected to high RH was not included, as it was outside the measurement range of the pressure gauge (290.7 kPa).

We also observed that materials with a higher burst index (NETT, MKs) are more sensitive to changes caused by both dry heat and high RH (Figure 2).



» **Figure 2:** *Burst index of the materials before and after exposure to dry heat* and high RH***

Conclusions

This study was conducted in order to investigate targeted properties of the paper-based materials that could be used (or already are in use) for making custom preservation enclosures. Since not all information on materials is covered by international standards and technical specifications, additional methods needed to be employed.

Selective investigation of the materials' properties was carried out to evaluate smoothness, water absorptiveness, water wettability, water vapor permeability, tensile strength, folding endurance, bursting strength, puncture strength, as well as loss of bursting strength caused by dry heat and 100% RH.

By observing the results, the following was concluded:

- Smoothness, water absorptiveness, water wettability and WVTR results obtained from ING confirm that a material outside of ISO 16245:2009 grammage requirements (90 g/m² instead of 100 g/m²) for making file covers can exhibit more desirable properties than the one that meets multiple standards for storage and preservation (VERG).
- Bursting strength of the materials was significantly affected by both high humidity and dry heat. However, high RH had a bigger impact on bursting strength of the investigated materials.
- Despite its hydrophilic behaviour, the surface finished material (ELF) shows both the lowest water absorptiveness and the lowest WVTR compared to other materials of similar grammage.
- The results do not indicate the need to perform both puncture and bursting strength tests, as they result in similar relations between the investigated materials.
- Determining the contact angle did not provide an insight into water absorptiveness and barrier resistance to water vapor of the materials, so it is advisable to exclude it from future analyses.

To conclude, the presented procedure proved to be a useful indicator of materials' properties within the context of heritage collections preservation and storage.

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Business models transformed by digitalization in contemporary art museums and galleries

ABSTRACT

In the 21st Century, the common features of the developing digital technology are compressed information, accelerated information management, big data, multiple interaction, personalization and uninterrupted access and convergence. These features are seen as factors that accelerate access to information, reduce some communication and cost expenses economically, speed up sales and marketing, provide visibility to institutions, and increase ideas and sharing. With the effects of digital technology Contemporary art museums and galleries have experienced digitalization processes in order to maintain their existence and achieve their goals. Digitalization is not limited to being a technical application, but it is a process that transforms contemporary art institutions as a whole, especially in communication, institutionalism, branding, marketing, finance and sustainability. Therefore, digital technology requires to be available to institutions. Being a contemporary art institution requires being intellectually and technologically renewed in institutional, managerial and communicative terms. The mission and sustainability of art and art institutions should be ensured in harmony with technology. Therefore, new business models have been required in the digitalization processes in art institutions and the need for changing business models will increase as technology develops. Purpose of the study: To identify the new business models of contemporary art museums and galleries, and in parallel, the features they need in human resources, and to raise awareness on this issue. In this study, the hybrid structure of new business models needed in contemporary art institutions has been revealed as a whole. In the study, it has been revealed based on the examples and the viewpoints of authorized persons that, managerial digital strategies in contemporary art museums and galleries should contain the distinction specific to art. The main result that emerged from the interviews is the hybrid structures of the new business models needed by contemporary art museums and galleries in the digital age, blended with digital technology and the knowledge of art management.

KEY WORDS

Digital technology, contemporary art museums, contemporary art galleries, digital strategy, digital business models in art Institutions

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Introduction

In the 21st century, the continuously evolving nature of digital technology and digitalization processes have canalized business models into a direction that requires digital competencies. As well as the yields of digital technology, contemporary art institutions are surrounded by areas such as global competition, institutionalization requirements, and creating a contemporary art environment. Therefore, it can be argued that these

institutions are directly related to management, communication, marketing, sociology, informatics disciplines, art history, art criticism and need digital competencies in all these subjects. For example, contemporary museology has an understanding that envisages new business models for museum staff in many fields such as creating collections, exhibiting, preparing archives, museum management, museum marketing, preservation, and storage (Karadeniz, 2018:pp.78-79).

In addition, as Yücel asserts, as institutionalization becomes faster, accurate, powerful, and systematic, the fields of expertise increase more. As the service areas of contemporary art museums and galleries diversify and institutionalization gets strong, specialization will increase. The need for new business models will increase.

The widespread use of IT and rapidly developing digital technology have caused museums and some galleries to define new business models that require digital skills such as experience director and digital director. According to Borusan Contemporary manager Kumru Eren it is necessary to gather the areas where new business lines are needed under three main headings as the presentation of exhibitions and works, commercial activities, and communication. First of all, with the development of technology, works that are only visually displayed on the internet can now be visited in virtual tour format of the exhibition spaces by laser scanning method.

The development of technology has enabled the works to be experienced more comprehensively with Augmented Reality and Virtual Reality technologies and the use of these technologies in the production of works. Moreover, the integration of voice guide applications into mobile devices provides a more comfortable experience for visitors. Also, the development of electronic commerce and the developing electronic marketplaces bring the products offered by contemporary art museums and galleries to the wider masses.

Finally, the increase in the number of social platforms and the differentiation of their offered content structures also require institutions to produce communication and marketing content that will appeal to diverse audiences. Within this context, it can be maintained that new business lines have appeared for the provision of all these services.

Method

This study is examined in six sections. The introduction provides information about the research subject. In the second part, the method of the research is emphasized. In the third part, the importance of digital strategy applications in the managerial field of contemporary art museums and galleries is scrutinized.

In the fourth chapter, the literature is reviewed, and the works requiring digital competence that contemporary art museums and galleries need are discussed through the studies carried out on this subject. In the fifth section, the data obtained from the interviews with the contemporary art museums and galleries, which constitute the sample of the study, are examined by the content analysis method. In the conclusion part, a conclusion is held out in light of all the findings.

The Qualitative research method was used as the method, and in-depth interviews were conducted with the managers of contemporary art museums and galleries, which were determined as samples, via e-mail or digital platform. Qualitative research is research in which qualitative data collection methods such as observation, interview, and document analysis are used, and a qualitative process is followed to reveal perceptions and events in a natural environment in a realistic and holistic way (Yıldırım & Şimşek, 2006:p.39).

The institutions that constitute the sample of the study are Akbank Art, Arter, Arton, Baksı Museum, Borusan Contemporary, Elgiz Museum, Kasa Gallery Pi-artworks, Pera Museum, and Zilberman Gallery selected from Turkey. Interviews with the managers of these institutions will be presented as an appendix to Atiye'Güner's doctoral thesis titled The Effects of Digitalization on Contemporary Art Museums and Galleries, which forms the basis of this study.

The interviewers and interview dates from the sample institutions are as follows. Hüsamettin Koçan the founder and general director of Baksı Museum (13.07.2021), Firdevs Ev Şimşek the media and marketing officer and Behiye Bobaroğlu collection manager of Arter (29.07.2021), Oktay Duran the founder and general manager of Art On Gallery (30.06.2021), Kumru Eren the managing director of Borusan Contemporary (26.072021), Ayda Elgiz Güreli founder and the managing director of Elgiz Museum (19.08.2021), Derya Yücel the managing director of the Kasa Gallery (16.06.2021), Özalp Birol the general manager of Pera Museum (26.05.2021, Moiz Zilberman: owner and general manager of Zilberman Gallery (30.06.2021), Eda Derala Pi art Works gallery manager (25.06.2021), Director of Akbank Art Curator Zeynep Arınç (21.06.2021).

In the meeting; The following questions were asked to the interviewees: Which new business models are needed in art institutions with digitalization. How has your institution been affected by this? The answers received were analyzed by content analysis and descriptive analysis methods. A code name was given to each of the interviewers in the analysis table. The analysis will appear in Table 1 in the Finding And Discussion section. In addition, studies conducted in this direction in the literature were also examined.

The importance of digital strategies in contemporary art institutions

Two general approaches can be identified in digital transformation strategies. The first is the presence of digital talents within the company and the employment of sufficient IT specialists. This strategy can be described as defensive. Developing the digital literacy level of staff is imperative and it is a strategy that is oriented to maintain old activities on the basis of new technologies, rather than using the full potential of new technologies. In other words, this strategy is utilized to enhance the ongoing activities of digital technologies. The second strategy towards digitalization is to develop new products, processes, and business models using the innovative and disruptive features of digital technologies (Taymaz, 2018:pp.19-20). Although the successful implementation of this strategy is much more difficult than the defensive strategy, its economic and social returns are remarkably higher. In order for this strategy to be successful, it is necessary to develop innovative talents within the company and to actively participate in international innovation networks.

It can be stated that in the digitalization processes, the necessity of digital strategies in the administrative field for contemporary art institutions has emerged. The digital strategy to be implemented in the administrative field is fed through two channels: financial resources and leadership that can manage change (Krebs, 2016). The purpose of a digital strategy is a vision statement with objectives for the organization's digital programs, supported by adequate 'evidence-based' leadership resources, and utilized as a guide by management and operations (Morrison, 2019:p.15). To put it more simply, the purpose of the digital strategy is a vision and goal expression for the organization's digital programs, and it is essential to inform all employees and collaborators about the potential and benefits that digital technology can create in corporate governance and operations.

Digital strategy for art museums and art institutions is different from other types of strategies. The digital environment is volatile due to the rapid change in technology. Therefore, unlike other departments, strategic plans need to be regularly and radically reviewed, along with the digital programs offered by the digital operation (Morrison, 2019:p.3). Differences between museums and galleries may not be appropriate for the same type of strategy. Their financial instruments, sizes, missions, places where they position themselves on the global scale, and target audiences are different. For this reason, it can be asserted that different types of strategies are required for digitalization in contemporary art institutions.

Krebs (2016:pp.56-61), Head of the Socio-Economic Studies and Research Division at the Louvre Museum's Research and Collection Department, draws attention to the fact that many museums try to develop crowdfunding programs using digital tools to improve or develop their restoration or education programs. However, there is a very strong digital difference between museums, depending on their size, financial instruments, and digital capabilities. Museums should generate a solution to this phenomenon in order to ensure their sustainability. First, the problem of digital competencies should be analyzed on a regional or local scale. According to Krebs (2016:pp.58-59), in terms of digital competencies, there is a big difference between white-collar and blue-collar workers, for example between administrators and gallery staff. Museums should organize seminars to develop digital skills, as the Louvre does, and try to eliminate inequality.

The exact scope of digital may vary from one organization to another. Unlike many other industrial sectors, museums have routes of reaching their target audience both during a visit and through online digital media. Providing people with a unified experience before, during and after a museum visit is an interesting strategic opportunity. For most purposes, and for most organizations, the starting point for digital definition and a unified experience can be any public digital service, including kiosks, digital signage, internal digital transactions websites, apps, and social media accounts, and all processes that directly support them (Morrison, 2019:p.14). The same remarks can be made for a contemporary gallery. It is possible to argue that the digital strategy is not only a strategy for museums and galleries but also a local and unified perspective and network for the preservation and digitalization of the collection and the digital skills of professionals.

The digital strategy of museums and galleries depends on several factors, such as financial resources, and leadership that can manage change. Therefore, implementing a strategy related to digital strategy and digital competencies in art institutions such as museums and galleries is both necessary and difficult. Krebs (2016:p.57) articulates this challenge as linked to the general economic model of museums. The application of digital technologies and methods is necessary to engender the digital strategies of museums/galleries.

However, the impact of the introduction of digital tools into the museum/gallery sector on the workforce and economic models of museums and galleries is also a crucial question. Expeditious changes in the media and technology environment require financial resources for museums and galleries. Rapid changes in the media and technology environment make a certain type of strategic response necessary (Morrison, 2019:p.18). For example, it is possible to be agile and responsive in

changing areas, e.g., devices and interfaces, while investing in permanent foundations such as content infrastructure and capacity. Contemporary art institutions should generally deliver a very high-quality customer experience in the field. If a museum or gallery is failing to keep up with technological change and providing a poor online customer experience, it risks damaging its reputation with key stakeholders and customer groups.

According to Resch (2018:pp.89-92), art gallery management and most galleries are stuck with a communication concept based on regular news bulletins and advertisements in art newspapers and traditional methods, which fails to produce the expected added value. Customers in certain segments want clarity and transparency, low risk and personalized offers tailored to their motives. The solution to this problem can be found in galleries' usage of functional customer relationship management (CRM) technology such as Artbinder.com, Gallerymanager.com, and tailoring their marketing messages to target the right customer with the correct value proposition. Customer relationship management (CRM) is a system that has become widespread since the late 1990s, keeping customer information in a central database, enabling the identification of customers (and their needs), thus enabling the development of customer-specific applications (Taymaz, 2018:p.93). Software systems not only help to organize effective personalized approaches for clients but also can ease the workload associated with digital photos, biographies, press releases, catalogues, invoicing and PR tasks.

As emphasized by Kati Price (Price, 2016:pp.110-11), the Head of Digital Media and Publishing at the Victoria & Albert Museum, the website, virtual commerce, CRM, collection management and digital data management system, social media management are the domains which the main investment and resources should be allocated for a museum. Only through this parallel, one can build a persuasive digital experience that needs to be tailored to her/his organization.

Regarding museums, according to Erbay (2017:p.267), museums, the business world and educational institutions can be expected to work together in the future. Contemporary museology will have to change its management styles, business situations, institutional needs, contracts and business models according to the needs of the new generation. With respect to galleries, the increasing complexity of the art market, due to the competition of galleries with each other and with other institutions in the art market, requires an open organizational structure (Resch, 2018:p.53). Galleries should define clear roles, job positions, adopt the technology necessary to improve these processes and accelerate business exercises and propound their digital strategies. The business models proposal propounded for contemporary art museums can also be applied to contemporary art galleries.

Business areas requiring digital competence in contemporary art museums and galleries

Today, contemporary art museums are not only institutions that transmit information, protect, seek information, and serve the spread of culture and art. A contemporary art museum is a variety of curatorial projects, guided tours, screenings, conferences, performances, etc., organized for the purpose of education, training, entertainment, where the audience is involved in art events. It is like a multifunctional show venue where products are marketed as commercial enterprises (Birol, 2018). Contemporary art museums play a vital role in the economy and cultural tourism and compete in the leisure industry (Belenioti & Vassiliadis, 2017:p.115). In this respect, it is seen that contemporary art museums are in an interdisciplinary structure covering the fields of marketing, art management, communication, and informatics. This interdisciplinary structure has expanded the need for different business models and the rapid development in information technology has increased the significance of digital competencies.

During the interview conducted with Özalp Birol, the director of Pera Museum, it is expressed that in terms of both the activities of the institutions and the work patterns in the office, with the development and enrichment of the existing business model for museums by using digital opportunities, a new model which can be called hybrid has emerged which blends physical access with digital/virtual access. Herein, several examples are indicated, such as exhibitions that provide 3D virtual tours, digital exhibitions, conferences held on online platforms, symposiums, learning and film programs, transferring selected publications to digital media, changing office working hours, and the possibility of working remotely with digital access.

Today, it can be asserted that art galleries have similar functions with museums as institutions where works of art are exhibited, where they meet with visitors, are archived, create sectoral memories, and provide social benefits. In the report compiled within the scope of the *Istanbul Cultural Heritage and Cultural Economy Inventory 2010 (İstanbul Kültür Mirası ve Kültür Ekonomisi Envanteri 2010)* Project (Bakbaşa & Plancisi, 2017:p.7), the value production chain for the visual arts sector was constructed. In the report, art galleries and museums are in the same category as one of the crucial distribution domains in the visual arts sector. According to the report, art galleries were not only evaluated as sectoral initiators but also as actors that ensure the formation and trans-

Table 1

Job Areas Requiring Digital Competence (Mu.SA – Museum Sector Skills Alliance, 2017:pp.36-37)

Business Model Mission:	Digital Strategy Manager, she/he can also be defined as BIT consultant. Digital Strategy Managers reinforce a museum's technological and digital innovation. She/he is responsible for a digital transformation plan in accordance with the general museum strategy. Alongside the entire museum management, she/he is responsible for the top-level museum digital strategy and financial planning of technological resources. She/he plays a mediating role between internal museum departments and external stakeholders and can communicate effectively with a variety of different stakeholders, especially high-tech companies.
Business Model Mission:	Digital Cultural Asset Manager, Digital Asset Manager, Digital Curator, The Digital Collections Curator is responsible for implementing the digital strategy of collecting, storing, archiving, preserving, and making available digital collections.
Business Model Mission:	Digital Interactive Experience Builder, Interactive Experience Builder, Digital Interactive Experience Designer, Interactive Exhibition Designer, Digital Interactive Experience Builder designs, develops and implements innovative and interactive experiences based on audience needs, providing meaningful experiences for all types of audiences.
Business Model Mission:	Online Community Manager; Online Cultural Community Manager, Digital Communications Manager, Digital Media Curator, Visual Media Curator, New Media Manager, Social Media Specialist or Online Community Developer. The online community manager responds to the needs of both online and offline communities. Builds and manages accessible and collaborative online communities for all stakeholders (audience, colleagues in museums and the heritage sector, educational organisations, donors, sponsors, decision-makers, etc.)

Adapted from pp. 36-37 of Mu.Sa Report. Emerging Job Profiles for museum professionals

mission of contemporary art memory. This detection designates that today's contemporary art museums and galleries have different aspects, but they have the same motivation and mission and they are akin in terms of their functions. It can be claimed that the new business models that contemporary art museums and galleries require in their digitalization processes are alike.

According to the results of the *Mu.SA: Museum Sector Alliance research platform eCult Skills* project carried out between 2016-2019, four job profiles that require digital competencies have been identified for museum staff (Mu.SA – Museum Sector Skills Alliance, 2017). Business profiles ascertained for the success of museums in their digital transformation are Digital Strategy Manager, Digital Collections Curator, Digital Interactive Experience Developer, and Online Community Manager. In Table 1, business models that require digital competence and the missions of business models are delineated.

The changing business models in the galleries arose from the demands of gaining a place in the global market with the effects of globalization, competing and constituting a brand identity within this context. Changing aims and functions of galleries required them to be managed professionally. In this context, the above-mentioned differences between traditional art galleries, and new galleries that adapt to modernization are illustrated in Table 2. This difference is exhibited to explain the new business models that galleries need.

Table 2

Difference between Traditional and Contemporary Galleries (Resch, 2018)

Value Suggestion	Sale of Art Works	A Complete Range of Services
Customer Concept	1. Art lover 2. Corporate collector 3. Seller/Collector	Customer segmentation in three groups (Flamboyant, amateur, traditional)
Communication Concept	Traditional Channels (mail, e-mail, announcements)	Brand building, digital technologies
Income Concept	Sale of artworks	Attractive pricing Keeping costs low
Growth Concept	No concept of growth	Global prevalence
Competency Configuration	Authority in art history	Marketing and sales management
Organization Type	Focus on primary market; Gallery managers and assistants	Three-stage structure: storehouse, gallery, fine arts
Institution Concept	Artists and other galleries	Long-term relationships with arts and non-art organizations
Coordination Concept	Uncertain market processes without contract	Contracts with all partners, continuous revision of these relationships

According to new gallery understandings, competencies are quite important as the adoption of strong management principles increases professionalism in the art sector. Managers should be professionals who demonstrate both management knowledge and business ethics (Resch, 2018:p.53). To illustrate, typical blue-chip gallery staff consists of; sales directors, gallery partners, artist contacts, registrars, archivists, accountants, and a preparation/installation team. Galleries may also hire full-time staff or contract freelancers to assist with photography and marketing (Bunting, Allison & Handler, 2014:p.82). Sales directors, called gallerists, are responsible for the exhibition plans of the galleries, all the communication and educational projects of the galleries, and communication with the artists. Their duties are not limited to these, but they set relationships with customers and the public about the work of artists (Bunting, Allison & Handler, 2014:p.82). It can be supposed that they have a similar role to the curators in the museum and have the primary responsibility for communication within all areas. One of the most prominent functions of galleries is that they represent a group of artists of their choice. In addition to exhibiting and selling works of art, they are responsible for the representation and promotion of a group of artists of their choice (Bunting, Allison & Handler, 2014:p.85). It is also one of the functions of the galleries to organize educational curatorial works, including the work of the artist. To further this mission, galleries perform crucial tasks such as storing and maintaining artworks, lending to museum exhibits, sending works to other galleries, providing an image to the press and collectors, maintaining an artist's resume and bibliography, creating educational films, setting catalogs and prices (Bunting, Allison & Handler, 2014:p.81). All of these events create archive records that are actively used for the representation of artists. When pre-presenting gallery recordings for easy access, the gallery becomes the basic content in which information about an artist flows. As a result, experts in digital curation (compilation) are needed.

In the interview, Kasa Gallery manager Derya Yücel states that the most common problems faced by galleries are financial resources and human resources needed for digitalization. Galleries need people who specialize in digital technology.

Findings and discussion

Table 3 shows the new business models that the interviewed institutions consider necessary in the digitalization processes. There is an important situation that Kasa Gallery Manager Derya Yücel pointed out during her

Table 3

The new business lines that Contemporary Art Museums and Galleries need in their digitalization processes

KG	IT department A new area of expertise where art and digital space combine
PWG	Social Media Expert Piar and Digital Manager
PM	A hybrid business model where physical access in the office is blended with digital/virtual Access A hybrid business model where physical access on an activity basis is blended with digital/virtual Access Business models that make remote working possibly with digital access
A.R.T	People specialized in photography, video, and graphics People who have graduated from visual departments of universities, and high schools in the field of culture and arts, broadcasting and similar creative sectors and have experience in branches such as television broadcasting, design, cinematography
ZBG	Publishing service is constantly taken from online art organizations
BRSN	Business models needed for the presentation of exhibitions and works Business models needed in commercial activities Business models needed for digital communication Works providing technological services for the experience of products that can only be shown visually on the Internet in virtual tour format and for exhibitions experienced with AR and VR technologies Jobs giving support for integrating voice guidance apps into mobile devices Sectors that organize communication and marketing content due to their difference in the number of social media and the content structures they offer
RTON	Social Media Management e-commerce site expertise
AKS	Communication experts on digital platforms
ELG	Social Media Expert Expert in web design
BKS	Competent and foreign-speaking personnel in the digital world A workshop that provides digital information and training in and out of the institution

interview. Yücel states that experts are also expected to be trained in art management. Three of the institutions participating in the study pointed out that the digital technology experts needed in contemporary art museums and galleries should also be experts in the field of art and have academic training. Almost all of the contemporary art museums and galleries (8/10) participating in the interview desired the management of the networks they use in the communication function and their web designs to be organized by people who are competent in digital technology. Two people who participated in the interview stated that e-commerce experts are needed and expressed their desire that digital marketing content should be prepared by people who are competent in e-commerce. One institution participating in the interview remarked on its reception of online publishing services from outside. A museum manager who participated in the interview emphasized the importance of digital literacy and underlined the need to organize workshops to increase digital literacy inside and outside the institution.

The preservation and conservation of time-based contemporary artworks is an area that should consist of more featured and diverse components. Time-based media and digital art are characterized as artworks of a certain duration, including film, video, digital, audio, computer-based, web-based, performance, and installation art (Smithsonian Time-based Media & Digital Art, n.d.). These artworks consist of technology-based components that present specific challenges for preservation, documentation, placement, and purchasing. According to Glenn Wharton (2013) who served as a conservator at the Museum of Modern Art in New York between 2007 and 2013 and established a time-based media preservation program for video, performance, and software-based collections in the museum time-depended and digital artworks may change with each installation (Sanchez & Smith, 2013). Thus, it is important to document the stages of installation. In this way, the next generation of museum staff can use these documents to decide or at least know how it was established at different points throughout history. Including the artist's comments, whole details of the installation should be recorded, involving floor plans and wall surfaces for the exhibition, paint or carpet types, light levels, sound levels, and room size. This information should be located somewhere in the collection management database.

One of the interviewed institutions has articulated the emerging business model related to time-based media and digital art preservation and conservation as a new area of expertise that combines art and the digital field. One interviewer has described it as a hybrid business model in which physical access on the basis of events is blended with digital/virtual access. An interviewer has expressed it as the business model needed for the presentation and installation of exhibitions and works. The same interviewer has asserted that there is a requirement for business models that provide technological services for the works available to be shown on the internet to be experienced in virtual tour format and for the exhibitions experienced with AR and VR technologies.

Conclusion

In studies on new business models led by digitalization in contemporary art museums and galleries, it has been observed that museums and galleries require business models in three realms. These three subjects are related to the functions of contemporary museums and galleries gathered in three sections: preservation, research, and communication. Digital curation (compilation) can be considered as a business area that encompasses all three functions.

One of the crucial results arising from practice is; in museums and galleries, it is necessary to combine expertise in technology with art management education. This should be covered by digital strategies for new business models. It is necessary to specialize in IT and to recognize new areas of expertise that will combine technology and art disciplines in addition to emerging business models. For this, the need for academic education processes should also be taken into account.

The need for social media managers, who manage the web pages of these institutions and prepare content for digital platforms, in contemporary art museums and galleries has increased. However, it has become a necessity for these areas to consist of people who have received art education. The reason for this can be seen in the necessity that technology should not alienate the aura that art generates. Digital technology is necessary for a contemporary museum and gallery, but it should not prevent the perception of the art object and the unique aura that only its materiality can produce. For instance, the selection of digital technologies utilized for exhibition and communication purposes in institutions should be made by people who can construe works of art and know technology. In fact, what art institutions need is a technology that exists but is invisible. This technology should be a responsive one that can respond in different ways depending on its utilizer.

Conservators, curators, and staff who are responsible for the organization of exhibitions should not only be experts in theory and ethics in their fields but should also be deeply in touch with the material aspects of the work. This knowledge and experience are especially important in an exhibition of time-dependent and digital artworks, which require installation.

The aura of being physically confronted with the artwork/movements may require contemporary art

institutions to remain in a more integrated and hybrid space. Contemporary art institutions should invest in this area, anticipating that digital and physical interaction will cover a growingly integrated field. Within this regard, one of the strategies to be made is training that will strengthen digital literacy in institutions.

The digitalization needs of museums and galleries and the special situations arising from the existence of art have created new diverse business models that requisite digital skills. The interdisciplinarity of contemporary museology and galleries will continue to fabricate emerging business models that are constantly evolving in the fields of education/training, ICT, management strategic areas, exhibition design, and communication. As a strategic approach, developing new business models in consonance with the requirements and variability in the digitalization process in contemporary art institutions may be essential for the continuity of institutions.

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The extensions of revolution-bump mapping

ABSTRACT

Creating 3D computer-generated surfaces has long been a difficult challenge in computer graphics, particularly when portraying massive landscapes with extremely detailed surfaces in real-time. Despite significant advances in computer vision in recent years, there is still a great demand for improved realism and the capacity to edit computer-generated 3D surfaces in real-time. We propose three scalable and faster algorithms for creating extended, beveled, and chamfered patterns using only two textures and a simple shape box. The proposed techniques produce visually pleasing results in real-time while retaining optimal rendering performance and without increasing the mesh density of the shape box.

KEY WORDS
Per-pixel revolution mapping, image-based modeling, rendering technique, bump mapping, ray-tracing

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Introduction

Real-time rendering using traditional methods is still hampered by a large amount of graphics primitives (polygons and vertices) that the graphics card must calculate. This has an impact on the interaction of 3D scenes, particularly those with complex 3D objects. Image-based rendering techniques (IBMR) gained traction as an alternative to traditional polygon-based rendering approaches because they can show 3D surfaces in real-time at a low-performance cost while avoiding mesh densification. These approaches use textures to store a collection of geometry-related data that will be retrieved during the ray-tracing algorithm stage, hence bypassing the computation of geometry.

Our research focuses on revolution-bump mapping, a technique that falls under the category of image-based modeling and rendering approaches (Halli et al., 2010; Ragragui et al., 2018). Because it uses a simple shape box and two textures. The first texture is used to produce the revolution surface, while the second is utilized to provide

the microrelief effect. We were able to greatly refine this approach such that it could generate extended, beveled, and chamfered revolution objects while preserving the features on their surfaces. Our approaches take advantage of the fact that the surface revolution is modified without the need to recalculate the texture (shape map). On the other hand, we can control in real-time the effect of extension, bevel, and chamfer parameters.

Related Work

Texture mapping is a method of adding realism to a computer-generated 3D shape introduced in (Catmull, 1974; Heckbert, 1986). This technique is the simplest and oldest of image-based techniques. It aims to find the relation between the texture elements defined in the two-dimensional texture space and the surface defined in a three-dimensional space. In effect, it is a process that takes a surface and changes its appearance at each location using an image, function, or other data set. It should be noted that this technique was extended by Blinn and Newell (Blinn & Newell, 1976).

In 1978, Blinn introduced, in the article (Blinn, 1978), a method to achieve what is called bump mapping. The latter simulates the wrinkles of a surface without the need to modify the geometry of the 3D model. The normal of a given surface is perturbed according to the partial derivatives of the applied texture, called the height map. This texture is a simple grayscale image, which can be seen as an elevation map. The perturbed normal is then used instead of the original normal when shading the surface according to the Blinn-Phong model (Blinn, 1977). This method changes the appearance of wrinkles and micro-reliefs seen on the surface of 3D models. An improvement of the bump mapping is the normal mapping (Peercy, Airey & Cabral, 1997). Its principle is to use a texture to save not the variation, but the coordinates of the normal for each fragment and then use them in the shading model. The principle is to perform the calculations directly in the tangent space. This space is defined for each face of the mesh and keeps the normal unchanged.

Displacement mapping is the first method to use the height map to add detail to a surface (Cook, 1984; Lee, Moreton & Hoppe, 2000). It masked almost all of the defects in the bump mapping and the normal mapping, as the surface geometry is completely changed instead of just disturbing the normal. This approach is based on the subdivision and the displacement of the sub-polygons of the surface along the normal to the vertices based on the distances obtained from the displacement map. The result is a more realistic rendering where the displaced geometry is also visible in the silhouette. The subdivision of a base surface considerably increases the number of graphic primitives (vertices and polygons) that the graphic map must manage, and this influences the execution time in the rendering stage. From there, research is focused on alternative rendering methods based on mesh simplification and ray tracing algorithms. The techniques presented in (Gumhold & Hüttner, 1999; Doggett & Hirche, 2000) took a different approach, their methods truly modified the geometry in such a way as to minimize the number of triangles rendered as a function of viewpoint. They proposed to use an adaptive subdivision for the displacement map to limit the number of polygons generated.

Per-pixel displacement mapping is an interesting improvement of the per-vertex displacement mapping technique introduced in (Patterson, Hoggar & Logie, 1991), the strong point of this approach is that it increases the realism of the surface without densifying the mesh. This method aims at solving the bottleneck caused by the very large number of graphics primitives sent by the vertex displacement mapping to the graphics processor (polygons, 3D points, normals, texture coordinates...).

Parallax mapping not only disrupts the normals but also changes the texture coordinates used, without changing the geometry of the object (Kaneko et al., 2001). Its principle is quite simple, it aims to shift the texture coordinates to perform an approximate search for the point of intersection between the view radius, expressed in tangent space, and the relief stored in the height map. To overcome the problems of simple parallax mapping, Welsh introduced parallax mapping with offset limitation (Welsh, 2004). A better improvement of the parallax mapping is called the Steep Parallax Mapping. It consists in assuming that the surface is always flat, but its normal vector can be arbitrary (McGuire & McGuire, 2005).

Binary search is a method specifically designed to converge quickly to the point of intersection to ensure fast rendering. This technique assumes that the actual intersection point is either at the top or bottom of the relief depth value retrieved from the displacement map (Policarpo, Oliveira & Comba, 2005).

Ray tracing uses the viewing ray to determine the point of intersection. It is also called linear search. It has been used alone in parallax mapping (McGuire & McGuire, 2005), as well as in (Policarpo, Oliveira & Comba, 2005) and (Tatarchuk & Natalya, 2006) as a first step.

Relief mapping is among the popular methods of real-time rendering since it quickly converges to the point of intersection that lies between the view ray and the relief (Policarpo, Oliveira & Comba, 2005; Policarpo & Oliveira, 2006). This is an extension of another technique called relief texture mapping (Oliveira, Bishop & McAllister, 2000). While this method will function and render satisfactorily in most cases, it may fail in some special situations. This problem will be solved

in (Oliveira & Policarpo, 2005), whose principle is to reinforce each vertex of the polygonal model with two coefficients representing a quadric surface that is locally close to the geometry of the object (Jean, 2002). This quadratic surface is used to produce correct renderings of objects and their silhouettes. Another improvement of relief mapping is proposed in (Ouazzani Chahdi et al., 2018) which is called dynamic relief mapping.

Sphere tracing uses spheres to converge most quickly to the intersection point. It was first introduced in (Hart, 1996) and then it was used for height map search using ray tracing (Donnelly, 2005). It is based on two main elements, namely the distance map and an iterative algorithm, whose goal is to find the first point of intersection between the view radius and the relief. Further improvements are presented in (Fabbri et al., 2008; Gustavson & Strand, 2011), whose objective is to improve the algorithm for computing the distance map.

Cone tracing is a technique that calculates the empty space, during the pre-processing phase, around each pixel of the depth map as an open cone at the top and then stores its ratio in a texture called a cone map. Subsequently, the cone map is used when searching for the intersection to converge more quickly on the intersection point without the risk of avoiding it. They exist in two versions, the first is a conservative technique (Dummer, 2006) and the second is a relaxed technique (Policarpo & Oliveira, 2007) coupled with a binary search. These two versions have been improved in (Halli et al., 2008). These improvements consist in using $O(n)$ linear algorithms instead of $O(n^2)$ quadratic algorithms to compute the conservative cone and the relaxed cone. Then calculate and store the radius of the cones instead of their ratio to have cone angles on the order of $\pi/2$ rather than $\pi/4$. Finally extend the technique to support non-square textures by using elliptical cone rectification during the rendering step.

Halli et al. introduced a new image-based approach for rendering revolved surfaces (Halli et al., 2009; Halli et al., 2010). Indeed, revolution mapping and extrusion mapping are based on a single RGBA texture that stores all the related data to the geometry. Then, the resulting texture is mapped on a shell box using 3D texture coordinates. This technique allows rendering full models and limits considerably the number of graphic primitives constituting the complex scenes. Further improvements of these techniques are presented in (Ragragui et al., 2018; Ragragui et al., 2020; Ouazzani Chahdi et al., 2021).

Revolution-bump mapping

The revolution-bump mapping uses a 2D binary form stored in the shape map, where only the zero-valued pixels constitute the base shape of the pattern that will be revolved during the rendering stage. This technique is based on ray tracing, and uses the Euclidean Distance Transform (EDT) computed from the base shape to skip the empty space and speed up the search for the intersection point between the viewing ray and the generated surface (Danielsson, 1980; Fabbri et al., 2008; Gustavson & Strand, 2011). It also relies on bump mapping to add realism to 3D objects by adding the illusion of microreliefs. The revolution-bump mapping makes it possible to considerably limit the number of graphic primitives constituting the complex scenes.

Revolution mapping

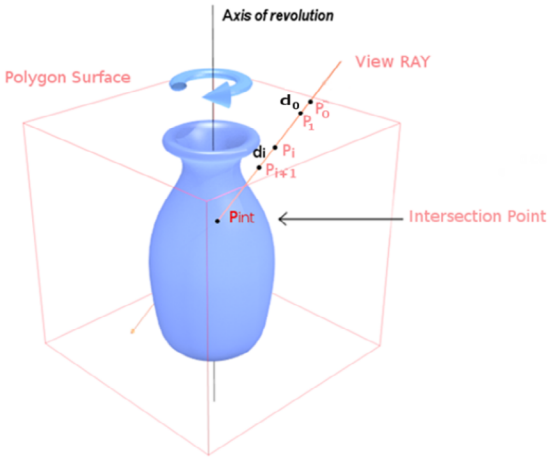
Per-pixel revolution mapping is an image-based modeling and rendering technique. It consists of generating very convincing surfaces of revolution without polygonization effect which are displayed interactively. The principle is to generate virtual surfaces using only a shape map that contains the geometry data of the basic form (Figure 1). This geometry represents the revolution of the basic form plated on the shape box using the texture coordinates (Figure 2). These coordinates are calculated using cylindrical or spherical projection. The revolution mapping is based on three main elements: the shape map, the ray tracing algorithm, and the shape box.

» **Figure 1:** *The shape map that will be sent to the graphic card*

Shape map is an RGBA texture that contains the data needed for the revolution mapping algorithms (Figure 1). The alpha channel is used to store the basic form represented by a binary image. The blue channel is used to store the distance map. Finally, the red and green channels contain respectively the x and y components of the gradient which will be used to determine the coordinates of the normal.

Ray tracing algorithm consists of searching for the intersection of the viewing ray with the revolved surface by using the distances stored in the shape map (see Figure 2). Let (u,v) be the coordinates of the current pixel and p_0 be the starting point of the search with the coordi-

nates $(x_0, y_0, z_0) = (u, v, 0)$, and let $\vec{V}$ be the normalized view direction determined by going from the viewpoint to the starting point p_0, all of which is expressed in the texture space associated with the current pixel.



» **Figure 2:** *Ray tracing process associated with revolution mapping. At each iteration, a circle tracing is performed to converge quickly and without the risk of skipping the first intersection.*

At each iteration, the minimum distance d_i between the point p_i and the revolved object is extracted from the blue channel of the shape map and a circle tracing is performed to advance to the intersection point without the risk of skipping the first intersection. The next point p_{i+1} is determined by the formula:

$$p_{i+1} = p_i + d_i \cdot \vec{V}_p \tag{1}$$

To retrieve the distance d_i between the current position and the base shape that is stored in the alpha channel of the shape map, the revolution algorithm uses the coordinates (s_i, t_i) (Figure 3). Using the following formula:

$$(s_i, t_i) = (\|\vec{R}_i\|, z_i) \tag{2}$$

With :

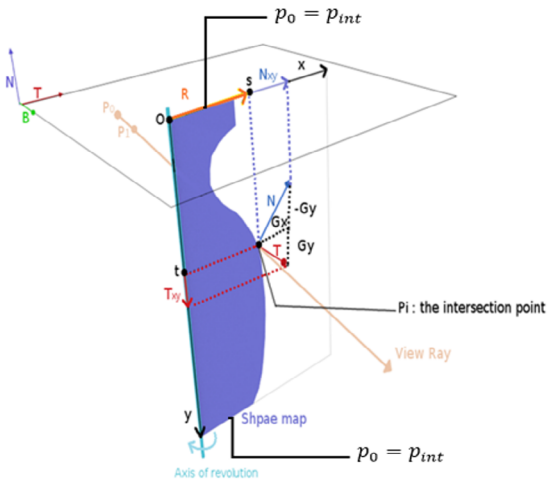
$$\vec{R}_i = (x_i - O_x, y_i - O_y)$$

From Figure 3, the normal is obtained from the components (G_{intx}, G_{inty}) of the gradient unit stored in the red and green channels of the shape map:

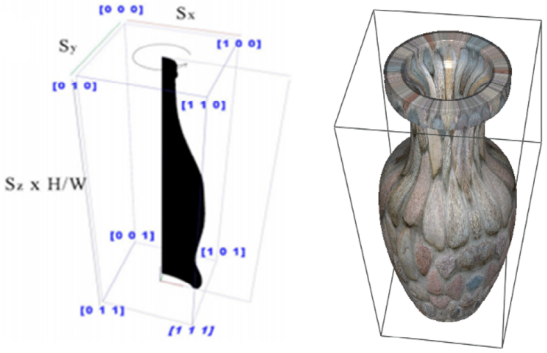
$$\vec{N}_{int} = \left(G_{int_x} \frac{R_{int_x}}{\|\vec{R}_{int}\|}, G_{int_x} \frac{R_{int_y}}{\|\vec{R}_{int}\|}, -G_{int_y} \right) \tag{3}$$

The shape box will be created from the shape map, as shown in Figure 4.a. *W* and *H* are the dimensions of the shape map. As well as *S* is a real-time editable vector, representing the scale of the shape box in the scene frame. The values in blue are the texture coordinates.

From figure 4.b we notice that the model is displayed in its entirety with a correct rendering of the silhouette.



» **Figure 3:** *The calculation of the normal and tangent at the intersection point.*



» **Figure 4:** *Creating the shape box. (a) Shape box that corresponds to the revolved object where the shape is placed vertically on the surface. (b) Rendering of a revolved object using the shape box.*

2. Calculation of the perturbed normal

The problem of revolution mapping is that the revolved object is created without any microrelief effect, so it does not take into account their realism. From this observation, the solution is to combine bump mapping with revolution mapping, which is called revolution-bump mapping (Ragragui et al., 2018).

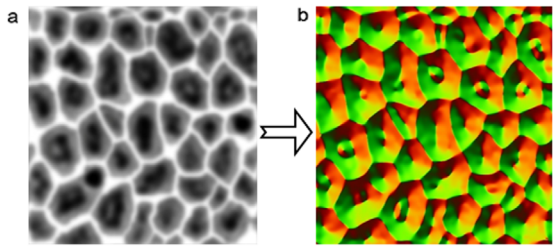
Revolved surfaces are created without any polygonal meshes and do not possess any parametric equation. Therefore, we must compute the tangent space associated with each intersection point. Therefore, the perturbed normal $\vec{N}'(u,v)$ is calculated from the sum of the normal vector $\vec{N}(u,v)$ and the displacement vector $\vec{D}(u,v)$ according to the following equation:

$$\overrightarrow{N'}(u,v) = \frac{\vec{N}(u,v) + \vec{D}(u,v)}{\left\|\vec{N}(u,v) + \vec{D}(u,v)\right\|} \quad (4)$$

With:

$$\vec{D}(u,v) = \left(\frac{a\,.\,\partial H(u,v)}{\partial u}(\vec{N} \wedge \vec{B}) - \frac{a\,.\,\partial H(u,v)}{\partial v}(\vec{N} \wedge \vec{T})\right) \quad (5)$$

The parameter a is a factor that can be controlled in real-time and is used to control the depth scale of the microrelief. The partial derivatives *∂H(u,v)* are computed along *u* and *v* of the height map *H(u,v)* in the preprocessing stage. Then they are saved in the red and green channels of a texture that we call the depth map (Figure 5).



» **Figure 5:** *The calculation of the partial derivatives of the height map. (a) The height map. (b) The depth map.*

This map will be sent to the graphic card during the rendering stage. Finally, the tangent can be deduced graphically using Figure 3:

$$\vec{T}_{int} = \left(Gy_{int}\frac{Rint_y}{\left\|\vec{R}_{int}\right\|}, -Gy_{int}\frac{Rint_x}{\left\|\vec{R}_{int}\right\|}, -Gx_{int}\right) \quad (6)$$

While the vector $\vec{B}_{int}$ is obtained by the vector product of the two vectors $\vec{N}_{int}$ and $\vec{T}_{int}$, using the formula:

$$\vec{B}_{int} = \vec{T}_{int} \wedge \vec{N}_{int} \quad (7)$$

The extensions of revolution-bump mapping

Extended revolution-bump mapping

Since the level lines of the distance map are extended forms of the base form, we can use them to create a surface of outside revolution. To do this, we simply replace the distance in the revolution-bump algorithm with the distance to the extended shape. Formula (1) becomes:

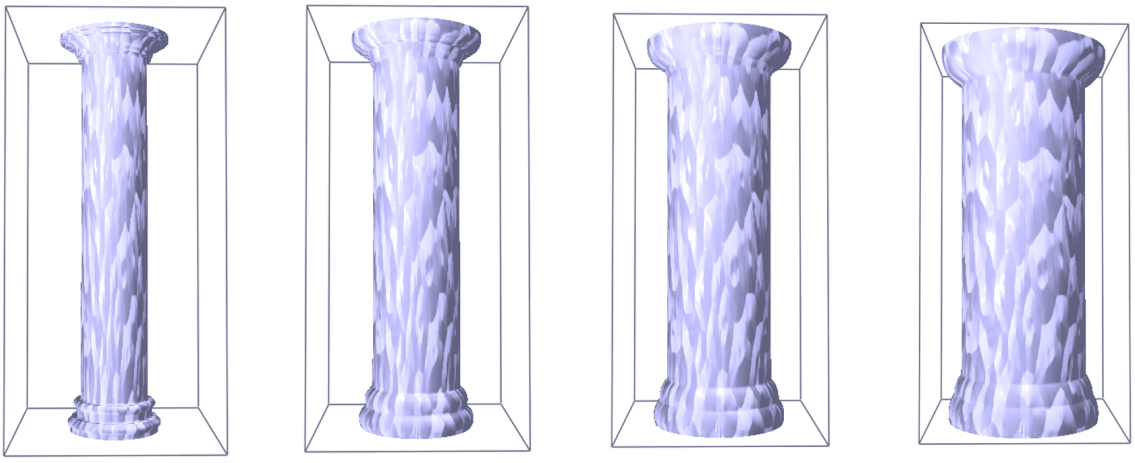
$$p_{i+1} = p_i + max(0, d_i - \mathrm{e}).\vec{V}_p \quad (8)$$

Where *e* is a parameter that can be modified in real-time, allow modulating the extension effect.

Even though the extended revolution-bump mapping is slightly slower than the revolution-bump mapping, it can be very useful for smoothing shapes as shown in Figure 6. It should be noted that for the extended revolution-bump mapping, the normal vector $\vec{N}_{int}$ and the tangent vector $\vec{T}_{int}$ remain the same as for the revolution-bump mapping, since the level lines of the distance map are extended forms of the base form (Figure 7).

2. Beveled revolution-bump mapping

The bevel consists of creating an outwardly extended revolution that varies as a function of depth. We start by searching for the intersection based on the distance to the original form by using formula (8) (because we are combining the bevel with the extended revolution-bump mapping). During this search, it



» **Figure 6:** *Rendering of an object using the extended revolution-bump mapping. These images are taken in real-time by changing only the value of the parameter* ***e****.*

is necessary to check if the current position is inside the geometry by using the following difference:

$$\Delta d_i = \max(0, d_i - e) - b \,.\, z_i \tag{9}$$

Where b is a parameter to control the effect of the bevel and Δd_i denotes the width of the bevel at z_i. The intersection point is determined according to the following system:

$$p_{i+1} = \begin{cases} p_i + \max(0, d_i - e)\,\vec{V}_p & If \quad \Delta d_i > 0 \\ p_i + d_i.\vec{V}_p & otherwise \end{cases} \tag{10}$$

» **Figure 7:** *Illustration of an example of the distance map that is stored in the blue channel of the shape map.*

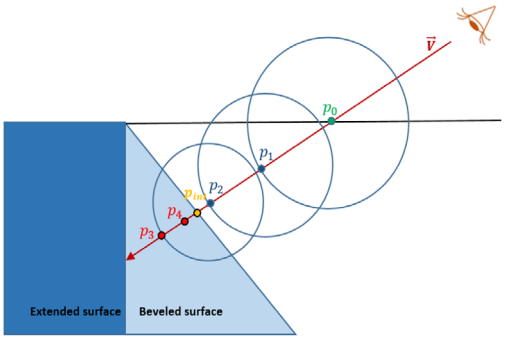
If Δd_i is positive, we calculate the next position p_{i+1} using equation (10), because the point p_i in the current step is always outside the geometry. If Δd_i is negative, we get the point which is inside the beveled surface like the point p_3 in Figure 8. Then we proceed to the binary refinement by successively dividing the last distance max $(0, d_{i-1} - e)$ by 2 to converge to the intersection point p_{int} of the geometry with the viewing ray $\vec{V}$ (Figure 8).

In contrast to the extended revolution-bump mapping, the z coordinates of the normal and y coordinates of the tangent must be changed. However, they remain uniform and are obtained by rotation of the gradient (Figure 9). The coordinates of the normal in this case become:

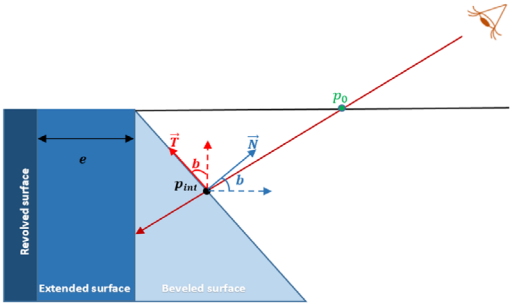
$$\vec{N}_{int} = \left(G_{int_x} \frac{R_{int_x}}{\|\vec{R}_{int}\|}, \; G_{int_x} \frac{R_{int_y}}{\|\vec{R}_{int}\|}, -b.G_{int_y} \right) \tag{11}$$

And the coordinates of the tangent are :

$$\vec{T}_{int} = \left(Gy_{int} \frac{Rint_y}{\|\vec{R}_{int}\|}, -b.Gy_{int} \frac{Rint_x}{\|\vec{R}_{int}\|}, -Gx_{int} \right) \tag{12}$$



» **Figure 8:** *The intersection of the viewing ray with the beveled surface.*



» **Figure 9:** *Diagram for the calculation of the normal vector and the tangent vector in the case of the beveled surface.*

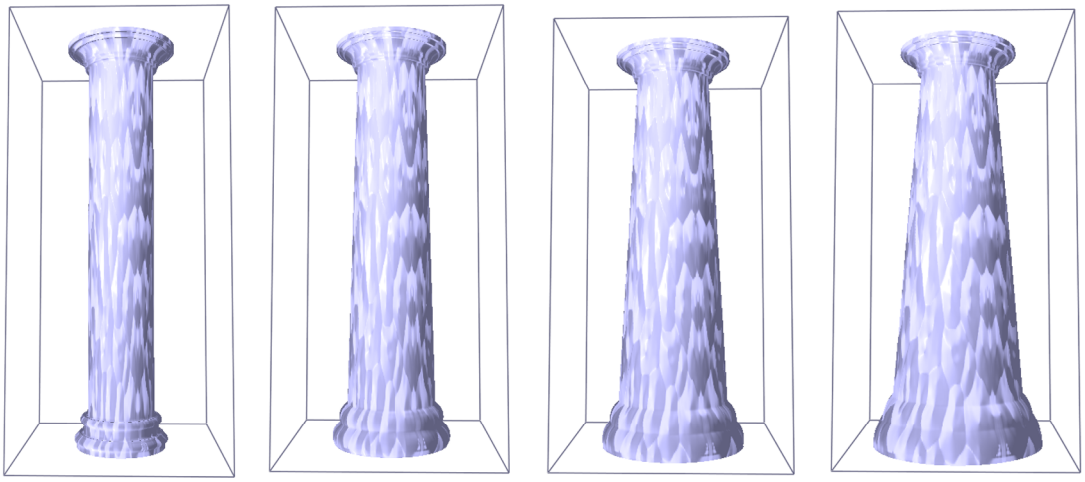
These two vectors, normal and tangent, must then be normalized before the perturbation of the normal $\vec{N}'_{int}$ by using formulas (4) and (5). As illustrated in the Figure 10, this enhancement enables for real-time modification of the revolution surface.

Chamfered revolution-bump mapping

The revolution-bump mapping with chamfer consists of limiting the effect of the bevel to a certain depth value to have edges with chamfer (Figure 11). To do this, simply replace formula (9), which defines the test above/below the beveled revolution-bump mapping, by the following formula:

$$\Delta d_i = \max(0, d_i - e) - b \,.\, \min\,(z_i, c) \tag{13}$$

With c is a parameter that allows modulating the chamfer effect. The modification of the z-coordinate of the normal must also be limited to the depth c. Note that the search for the intersection point is done according to the formula (10). For the revolution-bump mapping with chamfer, the normal and tangent will be equivalent to formulas (11) and (12) respectively if its depth is greater than the value of c in formula (13). Otherwise, these vectors are equivalent to one of the extended revolution-bump mapping.



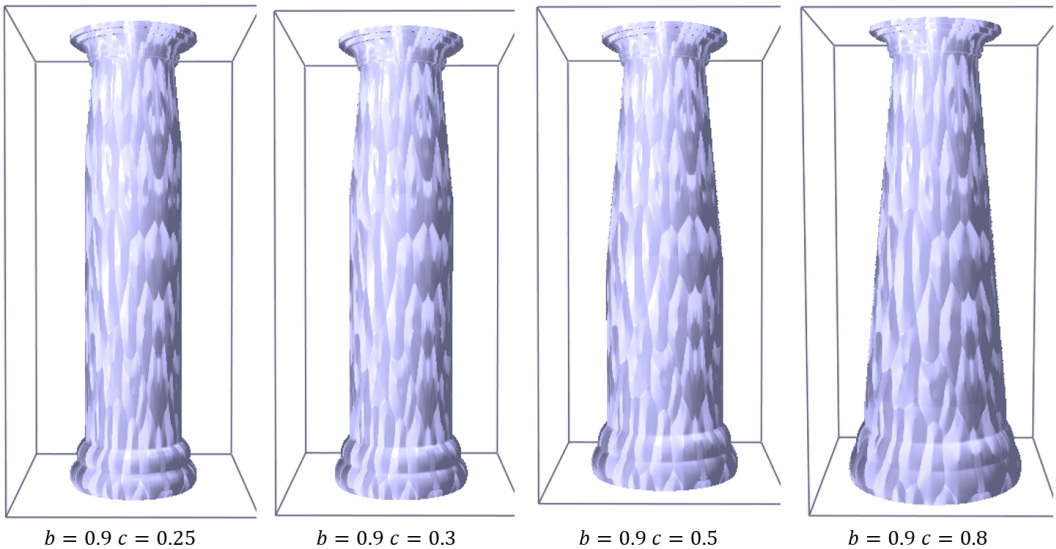
» **Figure 10:** *Rendering of an object using the beveled revolution-bump mapping. These images are taken in real-time by changing the value of the* ***b*** *parameter.*

Results and Discussion

To measure the rendering speed of the different techniques discussed in this paper, we have implemented the preprocessing stage of the algorithm that will compute the shape map and the displacement map in C++. After that, at the rendering stage, we have exploited the two programmable units of the graphics card (GPU), namely the Vertex Shaders and the Fragment Shaders using OpenGL associated with its parallel processing programming language GLSL. The measurements and figures presented in this section were performed using an Intel Core i7-3612QM 2.10GHz CPU architecture with 8GB of RAM and a GeForce GT 630M graphics card with 1024Mb of memory. Note that before starting the rendering, we send to the graphics card the shape map and the displacement map created during the preprocessing stage as well as the coordinates of the shape box.

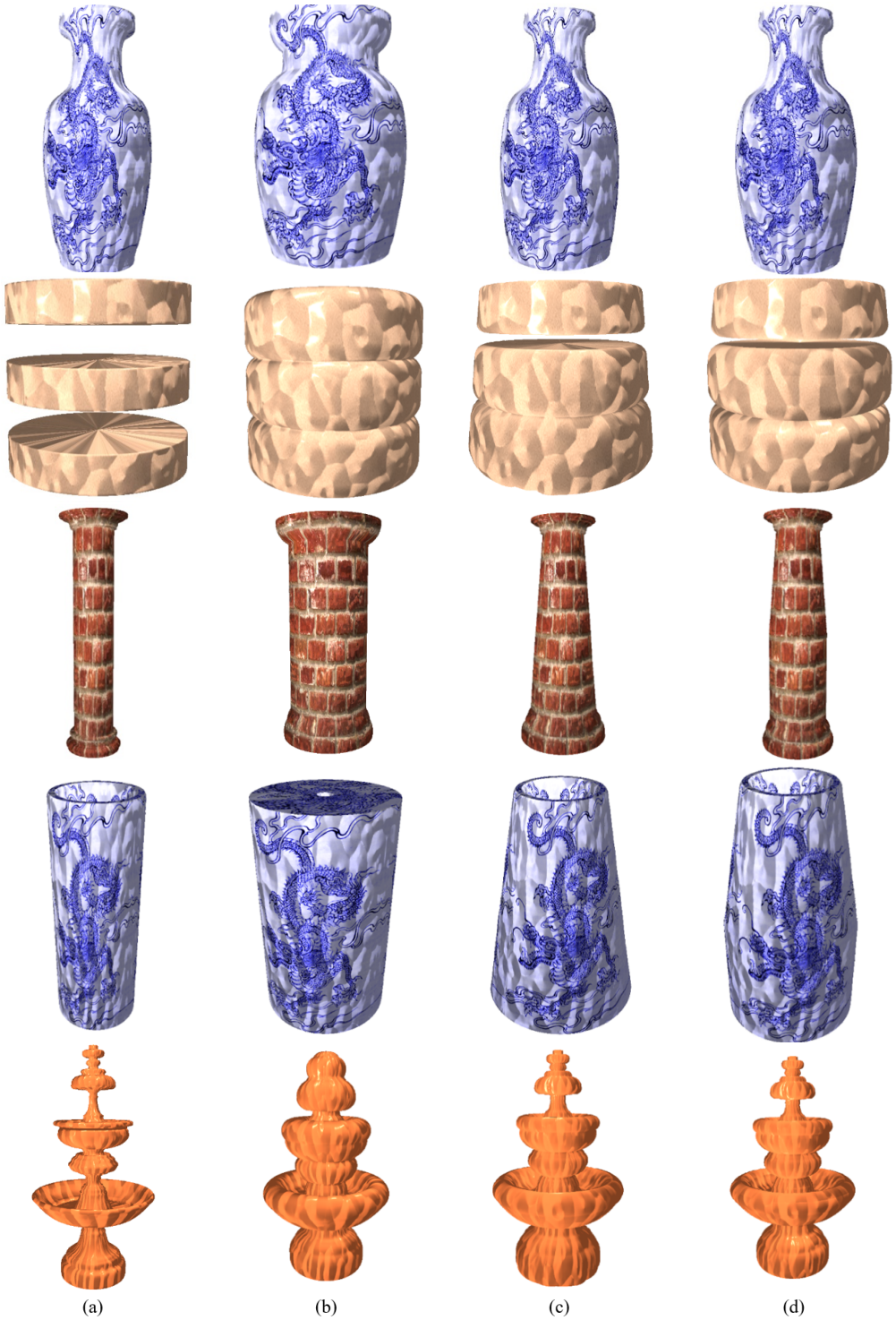
The images of the figures used to compare performance are rendered with textures resolution equal to or greater than 512×512, and with the microrelief depth scale parameter *a=1*. In addition, these images are screenshots taken during the test, and that the shape box occupies most of the screen. Note that the total number of iterations for the intersection search is 20. For the last two techniques, namely the beveled revolution-bump mapping and chamfered revolution-bump mapping, we set the total number of iterations to 10 for the binary search.

Figures 6, 10, and 11 show the techniques discussed in this paper. We notice that the images rendered by the

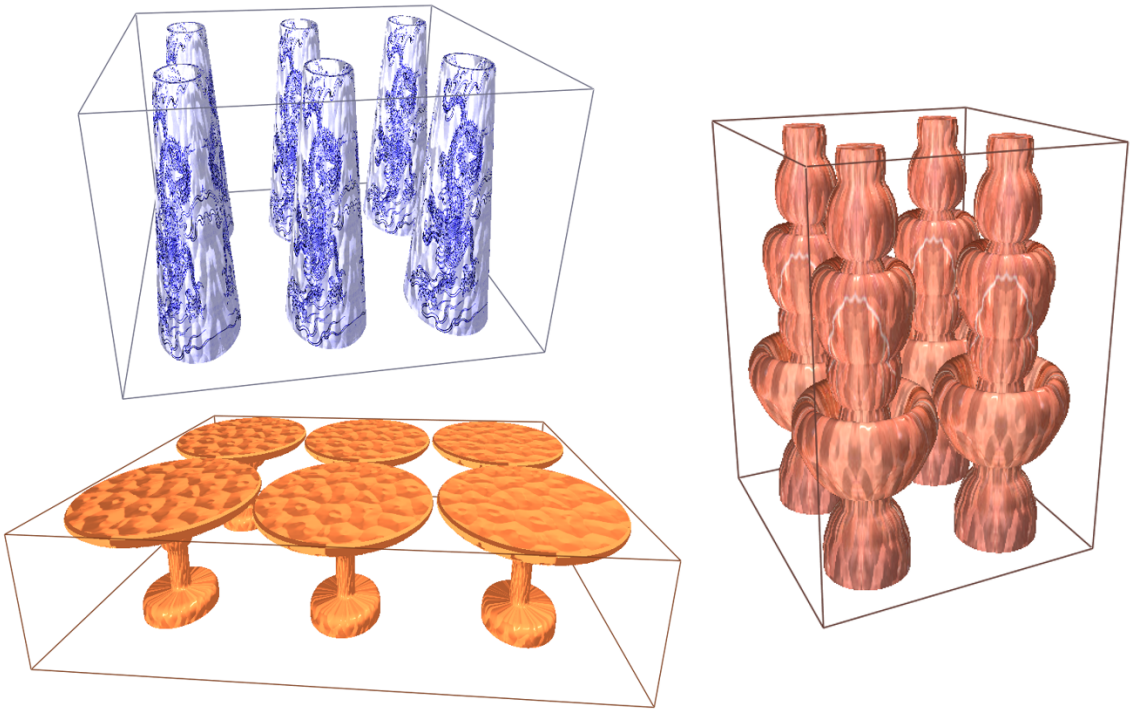


» **Figure 11:** *Rendering of an object using chamfered revolution-bump mapping. The images are taken in real-time by setting the value of* ***b*** *to 0.9 and changing the value of the parameter* ***c****.*

approaches proposed in this paper present realistic surfaces of revolution and that we can change them in real-time. Note also that the models created by these techniques present microrelief on their surfaces. Figure 12 shows a comparison between some models created by the different techniques discussed in this paper. These objects are obtained from a low-density mesh (shape box), on which a shape map and a displacement map have been plated. We can notice the variety of objects that can be created by these techniques and the change of the surface in real-time that we can control as well as the important number of graphical primitives (vertices and polygons) that can be avoided. The approaches discussed in this paper allow rendering revolved objects with a microrelief effect and without mesh densification.



» **Figure 12:** *Some objects were created using the techniques discussed in this paper. (a) Revolution-bump mapping. (b) Extended revolution-bump mapping. (c) Beveled revolution-bump mapping. (d) Chamfered revolution-bump mapping.*



» **Figure 13:** *Models rendered using extended, beveled and chamfered revolution-bump mapping with repetition.*

Figure 13 shows that the approaches presented in this paper can be also applied for the technique of revolution with repetition.

Table 1 shows a comparison of the rendering speed of the extended revolution-bump mapping with different values of the parameter *e* that extends the revolution surface, as well as the view on which the speed calculation is performed. We notice that the rendering speed of our approach decreases. This slowdown is due to the treatment concerning the enlargement of the generated surface, which is quite normal.

Table 1

Comparison of rendering speed in frames per second using the extended revolution-bump technique with different values of parameter e.

Model	Screen shot	e = 0,25	e = 0,5	e = 0,8
	800 x 600	180	170	160
	1366x706	150	145	130

Concerning the beveled revolution-bump mapping, Table 2 shows that the speed increases even if we increase the depth scale parameter *b*. This is because every time the value of *b* increases, the search interval of the intersection decreases, hence the number of iterations decreases.

Table 2

Comparison of the rendering speed in frames per second of the beveled revolution-bump mapping using different values of the parameter b.

Model	Screen shot	b = 0,25	b = 0,5	b = 0,8
	800 x 600	200	210	230
	1366x706	190	195	200

Table 3 shows a comparison of the rendering speed of the chamfered revolution-bump mapping by setting the value of *b = 0.8* and by varying the values of the parameter *c*. It can be seen that the speed increases when we increase the value of the parameter *c*. This increase is because we reduced the search interval of the intersection.

Table 3
Comparison of rendering speed in frames per second using different values of c and setting the value b = 0.8 using the chamfered revolution-bump technique.

Model	Screen shot	c = 0,25	c = 0,5	c = 0,7
	800 x 600	195	209	216
	1366x706	174	176	182

Conclusion

In this paper, we presented three new algorithms of the revolution-bump mapping technique that allow the creation of extended, beveled, and chamfered objects.

The proposed algorithms allow real-time control while maintaining the interactivity and visual richness of the created objects. The proposed algorithms allow real-time control while maintaining the interactivity and visual richness of the created objects. In addition, they avoid saturating the graphics pipeline, which can be caused by processing a very large number of vertices and polygons.

Extended, beveled, and chamfered revolution-bump mapping represent an interesting solution capable of providing control of the revolution surface and appreciable rendering quality. These techniques derive their advantages from the fact that they bypass the mesh densification because they use only a simple box, the tangent space associated with each intersection point, and two textures. The first texture is used to generate the surface of revolution while the second one is used to add the microrelief effect. The proposed improvements respect two objectives, namely the required rendering speed and the display of the revolution models in a very convincing way.

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Influence of hue and saturation on colour-shape association

ABSTRACT

A century ago, Wassily Kandinsky postulated that there was a strong and biunivocal correlation between elementary geometric figures and primary colours, respectively the most suitable associations were blue circle, yellow triangle, and red square. Most researchers did not find evidence in support of Kandinsky's combination, but rather in support of another combination: red circle, yellow triangle, and blue square (later called the "dissident" combination). And it was also found that the correlation was not strong, but rather medium. Until now, research has not focused separately on the influence of hue (at maximum saturation) on the appropriateness perception of shape-colour association, nor on the influence of saturation on the same perception. In view of this, two experiments were organized on samples of 546 and 461 participants that were all unaware of Kandinsky's experiment. The first experiment confirmed that hue influences the appropriateness perception of coloured figures, but also that, surprisingly, the shape-colour association was not biunivocal. The participants appreciated that the most appropriate associations were the red circle, the red triangle, and the blue square. However, the means of the appropriateness marks were not high. The second experiment proved that the appropriateness perception of coloured figures was directly influenced by colour saturation, and the correlation was strong (the correlation coefficient being between 0.71 and 0.94). Obviously, the experiments did not validate Kandinsky's theory.

KEY WORDS
Colour-shape association, colour, shape, Kandinsky's experiment

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Introduction

By the end of the nineteenth century, historicism had reached a major impasse and it was supported only by academic and traditionalist circles of the intellectuals and artists. The transformations in society, science and technology had caused some of the elements of historicism (such as ornaments, etc.) to lose their significance or to no longer be given the importance they once had. In the decades that followed, a diverse group of intellectuals, artists, designers, and others (gathered under the generic name of modernists) campaigned for a revolutionary change in several fields, including that of visual language. Modernists wanted to discover the intrinsic meanings of the elements of visual language, meanings that would be valid for any human being, regardless of the culture to which she/he belonged.

In addition to the endeavour to suppress historicism, the modernists wanted to impose a new aesthetic, built on rational grounds. The search for rational bases has not always been carried out with scientific rigor. Many statements of that period were based on the empirical reasoning of theorists. Usually, the approach of the modernists was wrong. First the idea was stipulated as an assertion, not as a hypothesis, and then it was verified, just formal usually. In the attention of modernists were the points, lines,

and colours, but also their combinations. Thus, the association between geometric figures and colours became the subject of theoretical speculation.

Analysed from the perspective of the present moment (a century later), the modernist thinking seems quite rigid and unjustifiably straight-forward. Some of the considered geometric figures that were analysed (the triangle and the square) existed only extremely rarely in nature, and a geometric figure much more present in nature, such as the hexagon (in honeycombs, basalt columns, etc.), was ignored. Thus, it is unlikely that these rare geometric figures in nature to be universally present in the human psyche, which has formed in nature or near nature over many millennia.

The first theorist who approached the theory of the biunivocal association of elementary geometric figures (circle, triangle, square) with the primary colours (red, yellow, blue) was Johannes Itten and since the time he was teaching at Bauhaus. It is known for sure which association he had promoted from a later work (Itten, 1970), namely: blue circle, yellow triangle, and red square.

The person who would stand out as a promoter of the association of elementary geometric figures with primary colours would be Wassily Kandinsky, known as an abstract painter, but also as a modernist theorist. Kandinsky had studied the physiology of colour perception, chromotherapy, psychiatry, and even occultism. Did his studies entitled him to approach with scientific rigor the field of association of shapes with colours? It is hard to appreciate today. What is certain is that he made a lot of stir with his 1923 experiment.

Many years before the famous experiment, Kandinsky wrote that yellow had an aggressive personality suitable for sharp shapes (triangle), blue was introspective and suitable for round shapes (circle), and red was vigorous and resistant (Dreksler, 2020). The speculative nature of the approach was obvious. Probably more appropriate would have been an association based on the order in the rainbow (for colours) and the order given by the number of sides (for geometric figures). Thus, the circle would correspond to red, the triangle to yellow, and the square to blue (combination that would later attract the attention of researchers).

In 1923, Kandinsky organized an experiment in two phases, different in scale: the first at the mural painting workshop and the second generalized within the Bauhaus. The experiment was based on filling a questionnaire asking for some elements related to the respondent's profile (job, gender, nationality) and then asking the respondent to fill a triangle, a square and a circle (all figures printed on a sheet) with yellow, red, and blue, so that each colour to be used only once. The criteria for choosing the colour were the appropriateness to the respective figure. In the end of questionnaire, a justification for the election was required. There are two initial aspects to emphasize: a) if the arrangement of the figures in a row or two influenced the results and b) if it was necessary to impose the use of each colour only once. Regarding the first aspect, Dreksler (2020) concluded that “shape location had no significant effect on colour choices”. About the second aspect, it was obvious that the respective instruction led forcefully to a biunivocal association, even if it did not really exist.

The experiment was obviously lead, the figures and colours being indicated in the "expected" order in the questionnaire (Lindsay & Vergo, 1994). In addition, everyone at the Bauhaus knew Kandinsky's postulate, so this "survey" could not be objective. Indicating another figure-colour combination meant to disagree with the great Kandinsky, or to disagree with the idea of logic in visual language.

It seems that one thousand questionnaires were run (Gage, 1995), but today only a few remained (Dreksler, 2020). Obviously, these are statistically insignificant. The author contacted by email the Bauhaus Archives about 20 years ago and received the answer that nothing remained of Kandinsky's experiment (personal communication, 2002). Recently, Dreksler (2020) received a more detailed response from the same organization, namely that there was a very low probability that something remained from the experiment.

Wassily Kandinsky has never published the detailed results of the experiment, but only publicly stated that the experiment had confirmed his theory. There was a lot to speculate since nothing remained of an experiment with one thousand questionnaires, not even a tally chart for example. Now somebody can only take Kandinsky’s word for it, i.e., that he obtained the results that confirmed his postulate.

At that same time, not everyone agreed with Kandinsky's associations. The painter and colour theorist Adolf Hölzel proposed his own combination, namely the red circle, the yellow triangle, and the blue square. Also, the well-known promoter of constructivism Liubov Popova supported the same association (Dreksler, 2020).

Apart from a few attempts to confirm or relaunch Kandinsky's combination, nothing notable happened until 1990, when Lupton & Miller (1991) sent Kandinsky's questionnaire to a group of industrial design professionals, teachers, and critics. Their responses varied according to their stylistic orientation- modernist or postmodernist. Two designers respected the questionnaire instructions and indicated the same correlation, but different of Kandinsky’s: red circle,yellow triangle, and blue square. But most respondents

did not comply with instructions and filled all the figures with brown or with spots of different colours.

After this moment, more and more researchers approached the topic of the association between elementary geometric figures and primary colours. As two combinations occur more often, they will be named in this paper according to the proposal of Dreksler & Spence (2019):

- circle blue, triangle yellow, square red- Kandinsky combination;
- circle red, triangle yellow, square blue - "dissident" combination (could be also named Hölzel-Popova combination).

The research was conducted in different parts of the world and involved different nationalities- Arabs, British, Chinese, Japanese, Romanians, etc. Summarizing in her thesis, Dreksler (2020) recalled that each experiment (except those performed in Romania- Dumitrescu, 2003; Dumitrescu, 2011) was performed with participants belonging to different ethnicities and different cultures. These parameters did not seem to be controlled properly. This situation would be justified if an objective association and not culturally biased would be find. But when the results were different in China (Chen, Jiang & Watanabe, 2019) and the United Kingdom (Makin & Wuerger, 2013), one can really draw a conclusion about the choices of different ethnicities given that the ethnic parameter was not controlled?

The applied research methods were different. Some researchers have used Kandinsky's classic questionnaire with three shapes and three colours (Jacobsen, 2002; Dumitrescu, 2003; Kharkhurin, 2012; Ghayouri & Ayat, 2020). Others extended the questionnaire to three shapes and four colours (Chen et al. 2016; Chen, Jiang & Watanabe, 2019) or to six shapes and six colours (Dumitrescu, 2003). Some researchers used the marks given by participants to the appropriateness of coloured geometric figures and bodies in all possible combinations (Dumitrescu, 2011). Implicit-association tests have also been used (Makin & Wuerger, 2013; Chen, Tanaka & Watanabe, 2015; Chen et al., 2016).

No evidence of a strong correlation between certain shapes and certain colours was found (Dumitrescu, 2003). But different researchers have noticed trends towards certain combinations. The combination that appeared most often as the true one was the dissident combination (Dumitrescu, 2003; Jacobsen & Wolsdorff, 2007; Dumitrescu, 2011; Chen, Tanaka & Watanabe, 2015; Chen et al., 2015; Chen et al., 2016; Chen, Jiang & Watanabe, 2019). Some research has found no evidence for the Kandinsky combination (Jacobsen, 2002; Kharkhurin, 2012; Makin & Wuerger, 2013), while others have been in favour of the Kandinsky combination (Ghayouri & Ayat, 2020). Exhaustively analysing the results of research in terms of replicated bindings, Dreksler (2020) concludes (in order) that the triangle is positively associated with yellow (without no negative association), the circle with red and the square with blue- which it is just the dissident combination.

Regarding some of the experiments performed for her thesis, Dreksler (2020) obtained different results after performing different experiments. Once the dissident combination was in the first place, the second time this combination was in an equal position to the one in which the circle was yellow, the triangle- red and the square- blue, and the third time the dissident combination was in a lower position. Shouldn't the results of the experiments be convergent? In addition, in one of the experiments, one third of the participants ignored the rule of using only once a colour in the associations. These aspects indicated that the hypothesis that there was a biunivocal correspondence between the elementary geometric figures and the primary colours was not validated by the experimental results.

In the research carried out so far, no special attention has been paid to the role of hue (at maximum saturation) and separately to saturation in the associations between elementary geometric figures and fundamental colours. There has been research (Chen et al., 2015) in which many colours have been used, but the emphasis has not been on hue and saturation. After that research, the conclusion was that the hard shapes were associated to cold colours and the rounded ones to warm colours. In turn, Dreksler (2020) observed tangentially that round shapes were less saturated and angular shapes were more saturated.

Method

Given that other research has found evidence to support the dissident combination (red circle, yellow triangle, and blue square) and that the influence of hue and saturation as variable parameters has not been directly studied, two objectives of this research have emerged:
1. To investigate whether the hue variation (at maximum saturation) influences the association of shapes-colours;
2. To investigate whether the saturation (for certain hues) influences the association of shapes-colours.

For the first research objective, the following hypothesis was established to be investigated: For each geometric figure considered, there was an intermediate colour between two primary colours that is the most advantageous to the figure. The research hypothesis for the second objective was: For each geometric figure considered, there is shade of a certain saturation of a primary colour that is the most advantageous to the figure. Thus, two experiments were organized.

Experiment 1

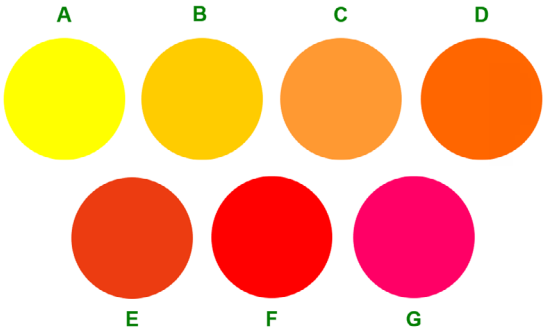
From previous research (Dumitrescu, 2003; Dumitrescu, 2011), whether people chose the shape-colour association that seemed most appropriate to them or they gave grades on a Likert scale to the appropriateness of figure-colour associations, it was observed that the highest values for associations (in both cases) were obtained for the red circle and the yellow circle; the yellow triangle and the red triangle and, respectively, the blue square and the red square. It can be hypothesized that the strongest association of a geometric figure with a colour is not manifested for a primary colour, but for an intermediate colour between the colours with the highest values.

To study this hypothesis, the colours on the base circle of Ostwald system were considered. For the circle and triangle, the following series of 7 colours was formed: yellow, red, four intermediate colours (20% red; 40% red; 60% red; 80% red) and pink as a random colour. For the square, the following series of 7 colours was formed: red, blue, four intermediate shades (red with 40% purple; red with 80% purple; blue with 80% purple; blue with 40% purple) and teal as a random colour.

For each type of geometric figure, an image was made that included the tinted figures in all the colours mentioned above. When analysing the possibilities of arranging the seven coloured figures in an image, it was found that there were practically only two relevant possibilities: an orderly arrangement with the gradual transition from one hue to another or a random arrangement. The first possibility was chosen, because it allowed the viewer a closer observation, respectively it sensitized the viewer to the hue gradation. It was also expected that this gradual transition would be found in experimental values. In each image, the seven figures were arranged in two rows: the first with four figures, and the second with three. It was decided to show each image alone to the participants in the experiment.

An example of an image used for assessment of circles is displayed in Figure 1. (The HEX codes for all colours used in experiment are indicated in Appendix 1.) The participants had to evaluate on a 5-point Likert scale how appropriate was the colour for the figure (1 = *not appropriate* and 5 = *perfect appropriate*). Regarding the selection of participants, it was decided that the participants should know the colour theory, but to be definitely unaware of Kandinsky's experiment. All participants' colour perception must be tested using Ishihara plates. The participants would be not financially rewarded for their participation in this experiment.

The lab conditions were decided to be the following. The laboratory was in semi-darkness provided by black curtains. Participants sat in chairs in front of desktop monitors. They waited in semi-darkness for 10 minutes before the experiment began. The monitors used were the same model, LCD with Led Backlight, 23.8-inch diagonal, Full HD, and 1920 x 1080 resolution. Before each session, a technician calibrated the monitors using a spectrometer.



» **Figure 1:** *Example of an image used for the assessment of circles with different hues*

The experiment session was designed to have the following structure: 1. The author made an introduction in which he presented the purpose and the methodology of the experiment to the participants. 2. Participants saw the coloured figures on computer screens and recorded their assessment using a survey administration software. The recorded assessments were transferred to a software spreadsheet (Excel), where they were processed.

Experiment 2

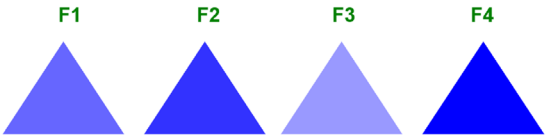
For the same reasons as in experiment 1, the question arose as to whether the most appropriate colour for a geometric figure could not be a colour of intermediate saturation. In experiment 1 as also in previous research (Dumitrescu, 2003; Dumitrescu, 2011), the colours were varied only in terms of hue and not of saturation. So, no data (raw or processed could be used in order to narrow the research like in the case of experiment 1. To study the hypothesis that the most appropriate colour for a figure is an unsaturated one, it was decided to use red, yellow, and blue with various saturations (100%; 80%; 60%; and 40%).

It was decided that in each image to be shown to participants, a single type of geometric figure should appear, but with different saturations. The order of the colours with various saturations was random in each image. (Experiment 1, which had been performed before the design of experiment 2, indicated that the graded variation of hue was not found in the experimental results, as seen in the mean values in Tables 1, 2 and 3.)

Thus, nine images were generated (3 images with circles; three with triangles; and three with squares). It was decided to show each image alone to the participants. An example of an image with blue triangles is displayed in Figure 2. Because in the previous experiment, some

participants were dissatisfied that the experiment lasted too long by giving a mark to each figure, it was decided to make this experiment quicker. So, the participants had to choose which colour-figure combination seemed the most appropriate to them for each image.

The selection of participants, the lab conditions and the experiment session design were the same as in experiment 1. (The HEX codes for all colours used in experiment are indicated in Appendix 1.)



» **Figure 2:** *Example of an image used for the assessment of blue triangles*

Results

Experiment 1

The experiment was carried-out with 546 participants (338 women and 208 men). All participants were students enrolled at a large technical university in Romania. The accuracy of results was tested using *Z-score*. No *Z-scores* were outside the interval [-3; +3], so no data sets were eliminated. The *Z-score* ranged between-1.56 and 2.10. The reliability of data was tested using the Cronbach's alpha coefficient. The calculated value for the whole set of data was $\alpha = 0.738$, value which stands for an acceptable reliability.

The results of the experiment 1 (appropriateness assessment on a 5-point Likert scale) were displayed in Tables 1, 2 and 3; respectively in Figures 3, 4 and 5.

The central tendency was towards the red circle, less from a mode point of view, but more considering the maximum value of the mean (3.64). However, the mean value of the red circle was not very high; it would have been desirable to be above the value of 4. Also, the standard deviation had a high value (1.18), indicating that there was a relatively large dispersion of results. Analysing the appropriateness assessment of triangles, it was observed that the central tendency was towards the red triangle, because of mode and mean (3.67) values. Again, the mean value of the red circle was not very high; it would have been desirable to be above the value of 4. And the standard deviation had a high value (1.18), indicating that there was a relatively large dispersion of results. What was surprising was that the same colour(red) resulted as appropriate for two geometric figures: circle and triangle. This seriously called into question the hypothesis that each colour had only one associated shape. Also, in the introduction to this article, it was pointed out that the instruction regarding the use of a colour one-time has forced the biunivocal association since the very first experiment.

Table 1

Results of Appropriateness Assessment for Circles in Experiment 1

Color	Mean	SD	Mode	Number of marks				
				"1"	"2"	"3"	"4"	"5"
100% Yellow	3.03	1.41	2	92	126	96	103	111
80% Yellow + 20% Red	2.86	1.07	3	57	149	158	139	25
60% Yellow + 40% Red	3.05	1.01	3	34	120	195	143	36
40% Yellow + 60% Red	3.24	0.96	3	19	95	194	179	41
20% Yellow + 80% Red	3.22	1.13	4	44	95	159	163	67
100% Red	**3.64**	**1.18**	**4**	29	70	110	166	153
Pink	3.10	1.39	4	103	80	102	147	96

Table 2

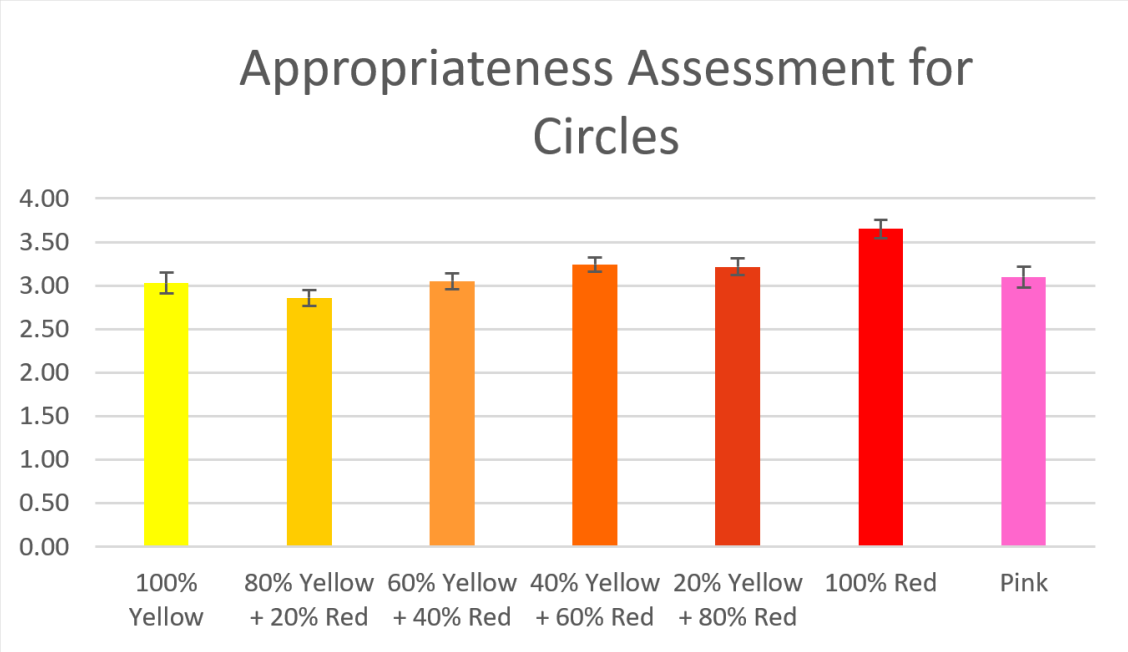
Results of Appropriateness Assessment for Triangles in Experiment 1

Color	Mean	SD	Mode	Number of marks				
				"1"	"2"	"3"	"4"	"5"
100% Red	**3.67**	**1.18**	**4**	32	67	96	186	147
20% Yellow + 80% Red	3.22	1.10	3.5	37	100	165	161	65
40% Yellow + 60% Red	3.22	0.96	3	23	88	207	171	39
60% Yellow + 40% Red	3.07	1.08	3	39	123	176	141	49
80% Yellow + 20% Red	2.77	1.08	3	67	157	160	118	26
100% Yellow	2.86	1.37	2	107	133	98	108	82
Pink	3.02	1.42	4	115	84	101	133	95

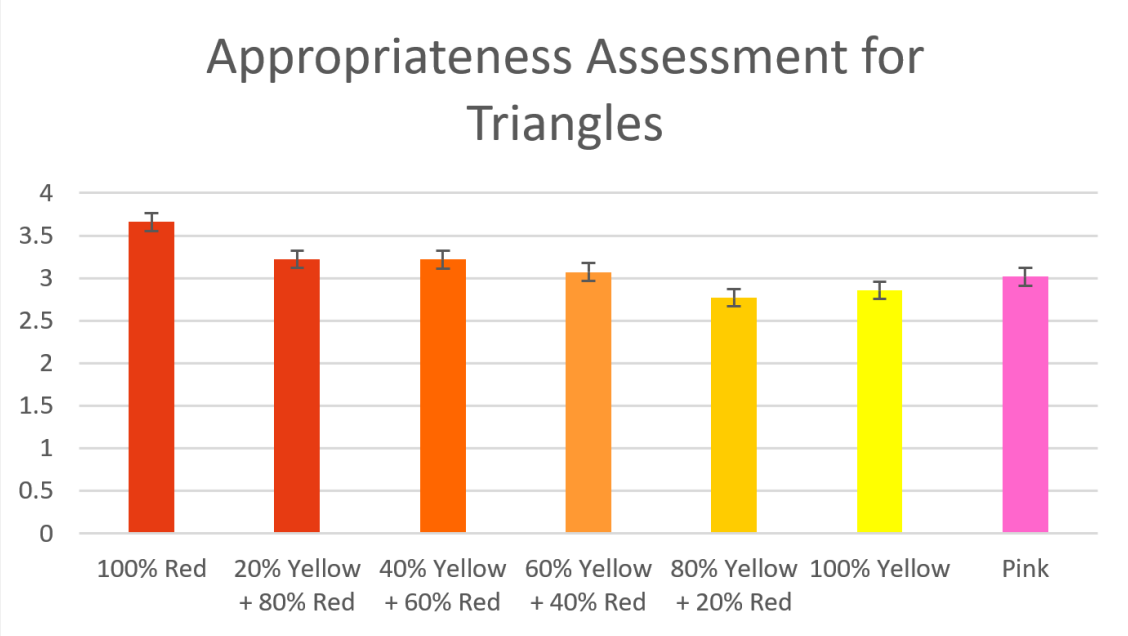
Table 3

Results of Appropriateness Assessment for Squares in Experiment 1

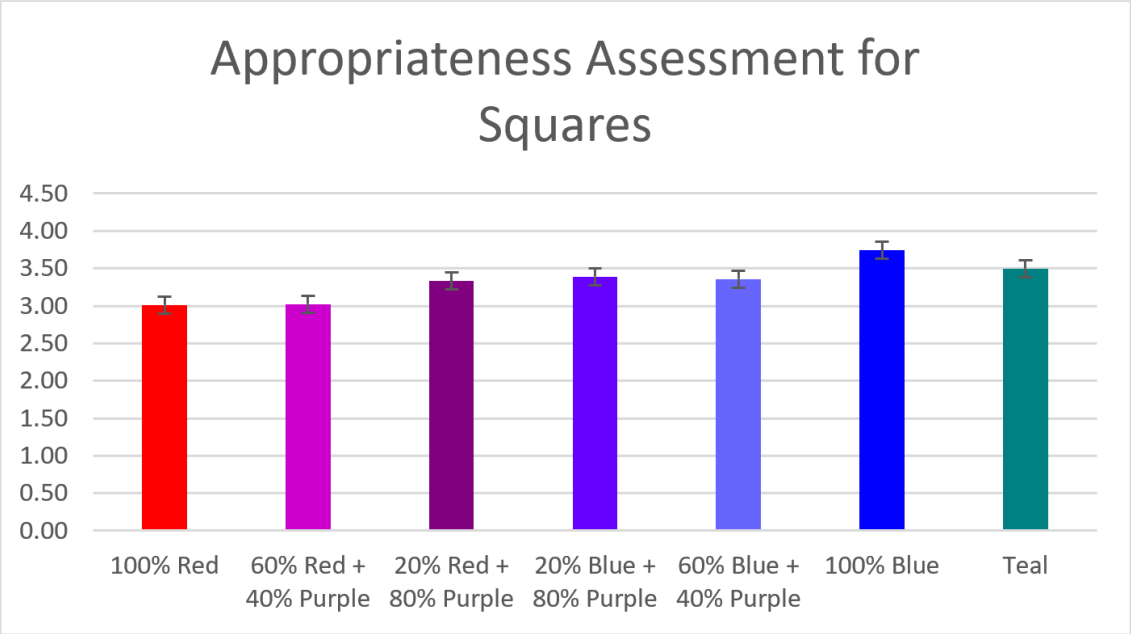
Color	Mean	SD	Mode	Number of marks				
				"1"	"2"	"3"	"4"	"5"
100% Red	3.01	1.30	4	91	98	121	149	69
60% Red + 40% Purple	3.02	1.25	3.5	72	118	132	137	69
20% Red + 80% Purple	3.34	1.18	3.5	38	95	149	144	102
20% Blue + 80% Purple	3.39	1.07	4	26	85	151	189	77
60% Blue + 40% Purple	3.36	1.02	3	20	82	186	169	71
100% Blue	**3.74**	**1.13**	**4**	25	55	106	187	155
Teal	3.50	1.13	4	29	79	122	195	103



» **Figure 3:** *Appropriateness assessment for circles.* Note: Error bars are 95% confidence intervals



» **Figure 4:** *Appropriateness assessment for triangles. Note: Error bars are 95% confidence intervals*



» **Figure 5:** *Appropriateness assessment for squares. Note: Error bars are 95% confidence intervals*

This finding can be correlated to the fact that in one of Dreksler's (2020) experiments one third of participants used one colour more than once. In the case of squares, the association that obtained the highest average was for a primary colour (blue square- 3.74), not for an intermediate shade. And again, the highest average was not very high, and the standard deviation was high (1.13). Since the difference between the highest and lowest mean varied between 0.73 and 0.89, the significance of this difference should be analysed more precisely. The recommended method of analysis was ANOVA single way. The following null hypotheses were formulated, applicable for corresponding data sets:

H01: The appropriateness of colour-figure is the same for all circles.
H02: The appropriateness of colour-figure is the same for all triangles.
H03: The appropriateness of colour figure is the same for all squares.

The results of ANOVA application were shown in Table 4. The null hypotheses were rejected on both grounds: *F* values and *p-value*. So, the associations circle – red, triangle – red and square – blue were significant according to this experiment.

Experiment 2

The experiment was carried-out with 461 participants (285 women and 176 man). All participants were students enrolled at a large technical university in Romania. The results of the experiment 2 were displayed in Table 5. At first glance, the number of choices of participants is much higher in the case of the maximum value of saturation.

Table 4

Results after application of ANOVA

F (1,3695)	p-value (<0.05)	F crit	Decision
23,79	9.39E-28	2.101	The H01 null hypothesis was rejected.
32,59	1.24E-38	2.101	The H02 null hypothesis was rejected.
26,06	1.6E-30	2.101	The H03 null hypothesis was rejected.

Table 5

Influence of saturation on shape-color association

Saturation	Circles			Triangles			Squares		
	Yellow	Red	Blue	Yellow	Red	Blue	Yellow	Red	Blue
100 %	258	254	213	233	269	203	204	264	231
80 %	98	71	89	104	70	105	143	82	88
60 %	41	47	79	70	56	68	54	60	78
40 %	64	89	80	54	66	85	60	55	64

Table 6

Results after application of Chi-Square test

X^2	p-value (<0.05)	X^2 critic	Decision
28.65	7.08E-05	12.59	The H04 null hypothesis was rejected.
36.61	2.1E-06	12.59	The H05 null hypothesis was rejected.
76.48	1.9E-14	12.59	The H06 null hypothesis was rejected.

Table 7

Correlation coefficients

Circles			Triangles			Squares		
Yellow	Red	Blue	Yellow	Red	Blue	Yellow	Red	Blue
0.84	0.71	0.81	0.91	0.78	0.84	0.94	0.84	0.85

To substantiate this observation, the following null hypotheses were formulated:

H04: The appropriateness of colour-figure is the same for all circles, regardless of hue and saturation.
H05: The appropriateness of colour-figure is the same for all triangles, regardless of hue and saturation.
H06: The appropriateness of colour-figure is the same for all squares, regardless of hue and saturation.

The Chi-Square method was used to test the three null hypotheses. The results after application of Chi-Square method were concisely presented in Table 6. All the three null hypotheses were rejected meaning that was a certain dependence between geometric figures, hue, and saturation.

The second aspect to be analysed was the possible correlation between the number of choices of participants (practically the perceived colour-figure appropriateness) and the saturation. The correlation coefficients were calculated for all nine coloured figures used in the experiment (Table 7). It was easy to observe that the correlations were strong and very strong.

Discussion

The research presented in this paper was conducted on relatively large samples of participants (over 450), so the results are consistent. Accuracy and reliability were also validated (when the data format allowed this).

Theoretical Implications

The first experiment aimed at identifying a saturated colour at an intermediate position between the primary colours to be associated with elementary geometric figures. The main finding was that the maximum marks for the colour-figure appropriateness were obtained for primary colours in all three cases. This justified the insistence with which modernist theorists and contemporary researchers have approached primary colours in such research. Surprisingly, for two geometric figures (circle and triangle) the same associated colour (red) resulted, which clearly indicated that the biunivocal association theory was not supported by experimental data. This finding came in conjunction with the fact that in one of Dreksler's (2020) experiments, third part of the participants chose the same colour for two different geometric figures. The maximum means of the marks for the three geometric figures were not very high. After applying ANOVA, it was found that indeed colour has a certain influence (obviously not great) on the perception of colour-figure appropriateness.

The second experiment was dedicated to the study of the influence of saturation on perception of association between shapes and colours. The results of the experiment indicated very clearly that the perception of colour-figure appropriateness was directly correlated with colour saturation (correlation coefficients being between 0.71 and 0.94).

Since from the beginning of the design of these experiments the classical question associated with this type of research has existed in the mind of researcher, the place of the answer is here, at theoretical implications. "Is Kandinsky's combination valid?" Given the results of experiments that seemed to be rather associated with the dissident combination (a combination confirmed by many researchers), the answer is obviously “No”. Then, the found association of a single colour with two different geometric figures undermines the very foundation of Kandinsky's theory, namely that of biunivocal correspondence between shapes and colours.

In the same direction, even Dreksler (2020) noted (in the paragraph “Dealing with the many inconsistencies”) that in simple experiments an association appeared, while in more complex experiments, that association was denied. Also, Dreksler (2020) writes in “Final Thoughts”: “This thesis has shown that surprisingly consistent associations can be found when stimulus sets, and task demands are restricted. [...] and the inconsistencies that

are often too easy to ignore in introductions and analyses when our focus lies simply on confirming trends."

Practical Implications

A practical implication of the experiment results would be that manufacturers should use saturated primary colours when designing products that are not only circular, triangular, or square in shape, but especially when strictly geometric character is important in terms of perception or possibly operation. However, the use of a certain colour for a certain geometric product should be validated by studying the target market segment, given that neither the Kandinsky combination nor the dissident combination is characterized by a high level of correlation.

Limitations and future directions

The results of this research were valid for Romanian young people, with a certain level of education. Additional studies are needed for possible extensions of the scope of research results.

The author has identified three promising areas of research:

1. Since an important field of application of the theory of shape-colour association is the manufacture of products, it would be interesting to study the shape-colour associations materialized in products, both two-dimensional and three-dimensional. The results would be very interesting, especially when beyond the abstract laboratory stimulus, the perception of the shape-colour association would be influenced by elements such as: product materiality, field of use, class of technology used (low or high), connotations of prestige and luxury and so on.
2. Kandinsky's theory was based on a subtractive chromatic system (with red, yellow, and blue as primary colours), a situation justified by the fact that one hundred years ago colours were studied using pigmented colours. Thus, a research direction would be to consider an additive chromatic system with red, green, and blue as primary colours. It is noteworthy that many experiments used Kandinsky's questionnaire, but the medium of application was the computer screen, which uses coloured lights, i.e., additive system. There were experiments that also used green, but the colour yellow was also presented and influenced the results (Chen et al., 2016; Chen, Jiang & Watanabe, 2019).
3. Given that people differ in many ways and not just demographically, it would be interesting to study whether people's characteristics related to perception or aesthetic education influence the perception of shapes-colours associations. One such feature could be Centrality of Visual Product Aesthetics (Bloch, Brunel & Arnold, 2003; Dumitrescu, 2021).

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Appendix 1

Colour	HEX
100% Red	#ff0000
20% Yellow + 80% Red	#ff3300
40% Yellow + 60% Red	#ff6600
60% Yellow + 40% Red	#ff9900
80% Yellow + 20% Red	#ffcc00
100% Yellow	#ffff00
Pink	#ff0066
60% Red + 40% Purple	#cc00cc
20% Red + 80% Purple	#990099
20% Blue + 80% Purple	#6600ff
60% Blue + 40% Purple	#6666ff
100% Blue	#0000ff
Teal	#0d9cb6
Yellow 100% Saturation	#ffff00
Yellow 80% Saturation	#ffff33
Yellow 60% Saturation	#ffff66
Yellow 40% Saturation	#ffff99
Red 100% Saturation	#ff0000
Red 80% Saturation	#ff3333
Red 60% Saturation	#ff6666
Red 40% Saturation	#ff9999
Blue 100% Saturation	#0000ff
Blue 80% Saturation	#3333ff
Blue 60% Saturation	#6666ff
Blue 40% Saturation	#9999ff

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