Brief Report

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Alone in the Dark? Modeling the Conditions for Visual Experience in Human Fetuses

ABSTRACT: *It is commonly assumed that, whereas auditory and olfactory learning take place already during fetal development, visual experience and learning are not possible before birth. This paper explores the conditions for visual experience in the last two months of human gestation, when the fetal visual system is mature enough to permit directed vision if a sufficient amount of light is available. Light transmission from the external environment to the uterine cavity is modeled, based on the measured transmission coefficients of biological tissues. Results indicate that illumination in the uterine cavity is highly variable, depending on factors such as external illumination and the mother's abdominal thickness. At least some fetuses can be predicted to develop in conditions allowing for ample visual experience before birth. This finding could have intriguing implications for the ontogeny of early visuo-motor abilities in newborns and infants. © 2010 Wiley Periodicals, Inc.* Dev Psychobiol 53: 214–219, 2011.

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INTRODUCTION

The uterine environment is a rich source of sensory stimulation for the developing fetus. Prenatal learning has been demonstrated in both the auditory (DeCasper & Spence, 1986; Moon, Cooper, & Fifer, 1993; Sai, 2005) and olfactory domain (Hepper, 1995; Mizuno & Ueda, 2004; Schaal, Marlier, & Soussignan, 2000), and has attracted considerable attention by researchers in developmental psychology and neuroscience. In contrast, visual stimulation in the uterus is assumed to be either absent or so reduced as to lack any practical effect (e.g., Glass, 2002, 2005; Lecanuet & Schaal, 1996; Myowa-Yamakoshi & Takeshita, 2006); see Jacques, Weaver, and Reppert (1987; Weaver & Reppert, 1989) for a rare exception. As a result, the possibility of prenatal visual experience and learning is dismissed a priori, and has never been systematically investigated in the literature.

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The present paper shows that, contrary to this widely held assumption, fetal visual experience is possible (though by no means universal or necessary) in the late phase of human gestation. Specifically, the last 2 months of pregnancy (postfertilization weeks 30–38/ postmenstrual weeks 32–40)[1] afford a time window in which the fetal sensory system is capable of directed vision if a sufficient amount of light is available. Empirical data on the light transmission characteristics of various tissues are used to model the amount of light reaching the fetus in late gestation. The model indicates that, in a range of plausible conditions, the inside of the uterus receives enough illumination to enable fetal vision. This result has fascinating implications for the study of early visuo-motor development, and could provide insight in the origin of individual differences in infant behavior.

Fetal Vision

The visual system matures relatively late in gestation, especially compared with the tactile, olfactory, and auditory systems. By weeks 20–22 the eyelids open in some fetuses, and the retina (especially the rods system)

[1] In the present paper, all gestational ages are postfertilization (typical pregnancy length: 38 weeks). Results from studies reporting post-menstrual age were converted by subtracting 2 weeks.

is already partly functional starting from weeks 12 to 17 (Fulford et al., 2003; Lecanuet & Schaal, 1996). Studies of premature neonates show that visual attention and fixation are present starting from 30 to 32 weeks, although artificial light stimulation can sometimes elicit physiological responses and evoke cortical potentials even in 26-week fetuses (Eswaran et al., 2002; Fulford et al., 2003; Kiuchi, Nagata, Ikeno, & Terakawa, 2000).

The fetal eye has a refractive error (RE) of about −5 diopters at 30 weeks, meaning that fetuses are myopic (Glass, 2002). At the same time, the amniotic fluid's water-like index of refraction adds a large refractive error on the hyperopic side, which more than compensates for fetal myopia (see Hallett, Speight, & Stinson, 1977). Fetal myopia decreases approaching birth, so that term infants are found to be slightly hyperopic (Cook, White, Batterbury, & Clark, 2003); however, some authors have argued that conventional RE measurement (retinoscopy) underestimates myopia in small eyes, and that term infants may actually be nearly emmetropic, that is, have RE close to zero (Banks, 1980; Glickstein & Millodot, 1970). Thus, fetuses may not suffer from large refractive error because the opposite effects of myopia and amniotic fluid refraction tend to compensate each other. Even the presence of some RE is likely to have only minor effects on fetal vision, since the spatial acuity of fetuses is low (Banks, 1980; Banks & Shannon, 1993; Glass, 2002) and their visual system has a long depth of focus (meaning that they see equally defocused images over a wide range of distances; Banks, 1980). Because of low acuity and defocusing, fetuses would only be able to see large objects or smaller objects at near distance, depending on what proportion of the visual field they cover.

The evidence just reviewed indicates that, starting from weeks 30 to 32, fetuses would be able to see—albeit with limited acuity—were they exposed to sufficient lighting. But how much light is needed to enable prenatal vision? Studies with newborns, both term and premature, suggest that their visual system works best at relatively low illumination levels (Glass, 2002), and that they are most comfortable with an ambient illuminance of about 50 lx (corresponding to a dimly lit room). Likewise, the optimal amount of light for fetal vision will be much lower than that of mature individuals. No published data are available on the minimum amount of light permitting vision in preterm infants; a conservative estimate of the threshold for fetal vision can be made at about 10 lx (i.e., enough light for an adult to read small printed text). In the following it will be argued that fetuses can often be expected to receive at least 10–100 lx, thus allowing for prenatal visual experience in the last 2 months of gestation.

MATERIALS AND METHODS

To estimate the amount of light reaching the inside of the uterus in various conditions, light transmission through various biological tissues (skin, adipose tissue, and muscle) and through various types of clothing was measured; the coefficients were then used to model intrauterine illuminance L_I as a function of external illuminance L_E.

Transmission coefficients were measured as follows. Seven 50 mm × 50 mm tissue samples were assembled from pre-cut, 5-mm-thick slices of muscle, adipose tissue and skin. Samples were obtained from avian tissues, choosing those most closely resembling the corresponding human tissues (in color and texture) as evaluated by a physician. Muscle thickness varied from 10 to 25 mm and adipose tissue thickness varied from 5 to 20 mm.

In order to measure light transmission, a black opaque cardboard pipe (150 mm length, 30 mm diameter) was sealed to a halogen light source of constant intensity. Tissue samples were fixed at the end of the pipe, and the transmission coefficient T was obtained dividing the illuminance measured at the sample surface by the illuminance measured at the same distance from the pipe, with the sample removed. All measurements were carried out in a darkened room (<1 lx) with a GBC brand digital luxometer (nominal precision: ±5%). Each sample was measured four times. The same procedure was then performed with various samples of cloth. Log-transformed transmission coefficients were estimated by multiple linear regression.

RESULTS

The estimated regression equation for the transmission coefficient T of the abdominal wall (one layer of skin, one layer of muscular tissue and one layer of adipose tissue) was:

$$\log_{10}(T) = -.942 - .058m - .032a \quad (1)$$

where m is muscle thickness and a is the thickness of adipose tissue (in mm). The overall transmission coefficient T could be estimated with high accuracy ($R^2 = .97$). In addition, the transmission coefficients of various types of cloth were estimated. Light, white cotton cloth has a transmission coefficient of about .50; black, thick cotton, and wool cloth have transmission coefficients of about .05.

A similar estimation procedure—also using samples of avian tissue—was followed in a previous study (Fulford et al., 2003) with similar results. The estimates presented here are more realistic, as the contributions of both muscular and adipose tissue were taken into account; only muscular tissue was measured in Fulford et al. (2003), yielding somewhat lower transmission coefficients (adipose tissue transmits considerably more light than muscle, as can be seen from the coefficients in Eq. 1). It should be noted, however, that the exact values of transmission coefficients are not critical; the aim of the present investigation was to obtain reasonable estimates of light transmission through the abdominal wall in order to build an approximate quantitative model. The qualitative results of the resulting model (Eq. 2) are robust, and would remain virtually the same even if the transmission coefficients were changed by a factor two.

Equation (1) can be rearranged—with the addition of a coefficient *c* representing the effect of clothes—so as to estimate intrauterine illuminance L_I as a function of external illuminance L_E:

$$L_I = cL_E 10^{-\left(.942+t\frac{.032+.058r}{1+r}\right)} \quad (2)$$

where *t* is the total thickness of the abdominal wall (in mm), *r* is the muscle/fat ratio of the abdominal wall, and coefficient *c* depends on the type of clothing (bare skin: $c = 1.00$; one layer of light cloth: $c = .50$; one layer of dark, heavy cloth: $c = .05$). In late pregnancy, when the mother's abdominal wall is stretched, total abdominal thickness in most women is between 20 and 40 mm, including uterine tissue (Fulford et al., 2003; Kiuchi et al., 2000).

Previous informal estimates of light transmission to the uterine cavity in mammals yielded values of about 2% (Glass, 2002; Jacques et al., 1987). The present model predicts that, with light-colored skin and no clothes, intrauterine illuminance should vary from about 1% to about 0.1% of external illuminance, depending on the mother's abdominal thickness. These figures can appear small, but they are actually rather large if one considers the range of illuminance in natural environments and the logarithmic scaling of light intensity perception. The human visual system works in a wide range of illumination levels, a range spanning five orders of magnitude—from moonlight (about 1 lx) to direct sunlight (up to 10^5 lx). When external illumination is in the upper range, even a very small fraction of it can be more than enough to enable vision in the lower range. For example, 0.5% of 50,000 lx (a typical value for indirect sunlight) corresponds to 250 lx, which is typical for an artificially lit room. This effect is compounded by the fact that the fetal system works best at relatively low illuminance levels, around 10^1–10^2 lx (see above). Another important consideration is that the estimated light transmission coefficients are weighted over the full visible spectrum, and are thus markedly conservative; the proportion of light transmitted by muscular tissue is much higher if one considers only the red portion of the spectrum (Fulford et al., 2003; Jacques et al., 1987), precisely where the immature visual system shows the best discriminative performance (Adams, Courage, & Mercer, 1994).

Figure 1 shows the levels of intrauterine illuminance (L_I) estimated in a range of plausible conditions. The most striking feature is the high degree of predicted variation in intrauterine lighting. In general, artificial illumination alone is not enough to enable fetal vision, but even the presence of a window can raise L_I to a sufficient level if the mother's abdominal wall is relatively thin. Direct sunlight, in contrast, is expected to enable fetal vision under a wide range of conditions. Another critical factor is the amount and type of clothing, which is expected to covary seasonally with external illuminance (i.e., higher illuminance and lighter clothes in warmer seasons). Of course, multiple layers of heavy clothing can filter out virtually any amount of external light; thus, the peak of intrauterine illumination during the cold season is probably reached when the mother is inside a warm, window-lit room. The mother's skin color can also have an effect; the present model assumes light skin pigmentation.

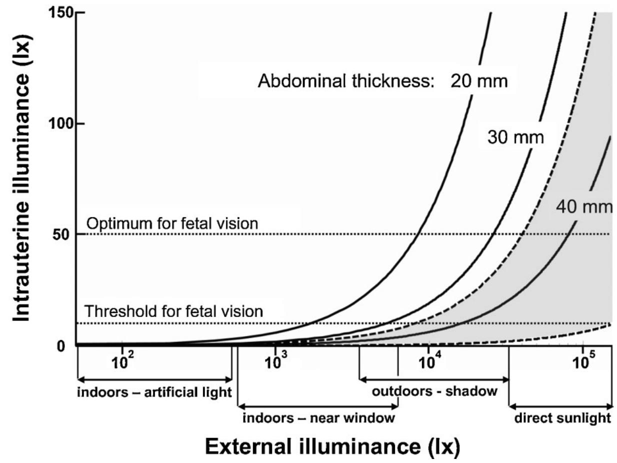

FIGURE 1 Intrauterine illumination as a function of external illumination and maternal abdominal thickness. Solid lines show the estimated function at three levels of abdominal thickness (20, 30, and 40 mm), assuming that the mother has a muscle/fat ratio $r = 2$ and is dressed in light clothes ($c = .5$). The gray area between dashed lines illustrates the effect of wearing different types of clothes, shown in the case of 40 mm abdominal thickness (upper dashed line: no clothes, $c = 1$; lower dashed line: one layer of dark, heavy cloth, $c = .05$). The typical range of external illuminance in various environmental conditions is shown below the graph.

As an example, consider a pregnant woman with an abdominal thickness *t* of 30 mm (about average) and a high muscle/fat ratio ($r = 2$), dressed in light clothes. When she is exposed to direct or indirect sunlight (about 3×10^4–10^5 lx), the fetus receives about 100–300 lx; this corresponds to the typical artificial illumination in houses, well above the hypothesized threshold for fetal vision. Indeed, such light intensity may even be *excessive* for optimal visual performance. For the same woman, being in a window-lit room (about 10^3–10^4 lx) would be already enough to permit fetal vision.

In summary, the simple model developed here predicts that some fetuses (those whose mother has a thin abdominal wall, and/or is approaching delivery during warm seasons) will develop in a remarkably bright environment, with ample opportunity for visual experience during the last 2 months of pregnancy. At the other extreme, some fetuses will experience a mostly or totally dark environment, allowing for little or no visual stimulation to occur.

CONCLUSIONS

The available evidence indicates that, during the last 2 months of gestation, most human fetuses are potentially able to see and to orient their attention toward visual stimuli. In this paper, an approximate model of light transmission through the mother's abdominal wall was constructed. Light intensity in the uterine environment is predicted to vary substantially depending on several factors, including external illumination and the mother's abdominal thickness. Using conservative estimates of the amount of transmitted light and of the minimum threshold for vision, the model shows that, in a range of plausible conditions, light intensity in the uterine cavity can be high enough as to permit fetal vision. The amount of illumination experienced by individual fetuses can vary considerably, ranging from virtually complete darkness to a surprising well-lit environment. The model presented here is a first approximation, and could be improved in many ways (e.g., direct intrauterine measurement, modeling of light transmission at specific wavelengths); however, the range of conditions enabling fetal vision is wide enough that minor changes in model parameters would not alter its qualitative results.

Another factor that may affect visual experience is the position of the fetus in the uterine cavity. In late pregnancy, about 90% of fetuses assume a head-down vertex position (e.g., Witkop, Zhang, Sun, & Troendle, 2008). About 80% of fetuses reach delivery facing toward the mother's back (occiput anterior), a position that would reduce the direct amount of light available for fetal vision; however, fetal positions before delivery are much more variable, and even in late labor only 27% of fetuses are already in the occiput anterior position (Lieberman, Davidson, Lee-Parritz, & Shearer, 2005).

The present results indicate that prenatal experience does not only affect auditory and olfactory development, but can also influence visual development when the required conditions apply—even if visual experience before birth is by no means necessary for the successful maturation of the visual system. Although direct evidence in humans is lacking, precocious visual stimulation may accelerate the development of visual functioning and enhance vision-related behavior after birth, as it does in rats and quails (Dumas, 2004; Foreman & Altaha, 1991; Lickliter, 1990). Accelerated visual development, however, may come as a mixed blessing: sensory systems mature in a precise sequence (ending with vision), and precocious visual stimulation has been found to interfere with olfactory learning in rats and prenatal auditory learning in qualis and ducks (Gottlieb, Tomlinson, & Radell, 1989; Kenny & Turkewitz, 1986; Lickliter, 1990). However, such interference effects do not seem to cause reduced auditory functioning, and (at least in birds) the delay in auditory learning can be compensated for by postnatal learning. This suggests that prenatal visual experience is unlikely to permanently disrupt the organization of other sensory modalities; nevertheless, the impact of precocious visual input on the development of earlier-maturing sensory system should be carefully investigated, as interference effects can be expected based on the animal literature.

Importantly, the main source of visual stimulation for a late-gestation fetus is provided by *his/her own movements*. Arm and leg movements in fetuses appear as soon as week 9, and by the end of the first trimester hand movements diversify to include a wide range of behaviors, with hands reaching to and making contact with face, eyes and mouth (Kurjak et al., 2003, 2005). There is evidence that fetuses at weeks 19–35 open their mouth before touching it with the hand, thus suggesting some kind of motor anticipation (Myowa-Yamakoshi & Takeshita, 2006); as early as 20 weeks, fetal hand movements begin to acquire kinematic properties suggesting rudimentary action planning (Zoia et al., 2007).

Receiving visual feedback on one's own actions and movements might have important consequences for fetal development. It has been proposed that infants form associative visuo-motor connections by synaptic Hebbian learning following repeated self-observation of movements, and that these associative processes contribute to the development of the mirror neuron system (Del Giudice, Manera, & Keysers, 2009; Heyes, 2010; Keysers & Perrett, 2004). Intriguingly, if a fetus was able to observe its own movements in the last months of gestation, it could develop a rudimentary mirror neuron system even before birth. Prenatal experience could thus contribute to individual differences in newborns' visuo-motor abilities—for example, infants exposed to higher illumination levels during pregnancy might show better coordination and/or imitation skills in the first weeks of extrauterine life. Conversely, the visuo-motor abilities exhibited by (some) newborns could be mistakenly described as "innate" in a strong sense (i.e., emerging without prior experience), when they actually result—at least in part—from prenatal visual learning. Of course, the above speculation is premised on the assumption that precocious stimulation actually results in accelerated visual development; it may well turn out that early visual stimulation has no such effect, or even that it interferes with later developmental processes, for example, recognition of parents' faces. In summary, whether prenatal visual stimulation is beneficial or damaging for perceptual development is an open empirical question.

The discovery that the uterine environment is rich in auditory and olfactory stimulation revolutionized the way scientists and laypeople look at prenatal life, and revealed a previously unsuspected world of active exploration and learning by the developing fetus. The possibility of prenatal visual experience and learning further expands this scenario and suggests fascinating avenues for future empirical research.

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