Headphone power levels and suitable amplifiers.

This article describes the relation between output power, headphone impedance, sensitivity and other factors that define audio reproduction in the headphone related area. It is not (completely) applicable for loudspeakers.

To make the article more readable for anyone the article is split with simple explanations for noobs on this page and the rest of the article is more technical.

The often read remark a headphone need LOTS of power is total nonsense nor the phrase 'hard to drive'. All (normal) headphones need about the same power. Due to differences in efficiency and impedance some headphones need a higher voltage and thus a lower current and other headphones need a lower voltage and thus a higher current. This article will give you an idea about HOW MUCH power, voltage and current is needed.

What do the terms mean used in the listed specifications of headphones?
These are the ones that matter.

**Frequency response:**
Forget the frequency response figures as these are usually a bunch of 'lies' for sale boosting purposes. In 99% of the listed frequency response 'data' the all important 'cut-off' points (where the graph falls below a certain value) is not given. Since most graphs have variations of several tens (not tenths) of dB's these figures are conveniently left out.

So a proper specified headphone that states 30Hz to 18kHz (-3dB) may have much deeper lows and have much more highs extension than headphones that simply state 10Hz to 50kHz or 20Hz to 20kHz as these points may lie 10dB or even 30dB below the middle part of the frequency range.

So best to forget the frequency response part as usually it only states 20Hz to 20kHz or something close to it. It's also not a very important figure, the graphs CAN tell you more about the sonic character but is not within the scope of this article.

**Power rating:**
Headphones have a certain (maximum) power rating. Usually around 200mW (0.2W) but headphones exist with power ratings of 1W to even several Watts depending on the construction and type of transducer (driver).

At normal listening levels these powers will never be reached and when played loud only very short peaks might come close to those levels. For normal listening levels 1mW to 10mW is more realistic so when the connected music source can only deliver up to 50mW it plays quite loud already (if the sensitivity is high enough).

*In general power ratings vary between 200mW to 500mW with a few exceptions of 1W or even several watts.*

**Sensitivity:**
Usually given in dB/mW or should be noted that way. Sometimes only dB is given or dB/Volt (dB/V).

In the case SPL/Volt or dB/Volt is given the efficiency figures need to be converted to dB/mW. This involves including the impedance of this headphone and is discussed below.

Sensitivity (or efficiency) basically tells you how loud the headphone sounds (at 1kHz) when a certain power or voltage is applied.

When given at 1mW a rating of 90dB/mW states there will be 90dB SPL (Sound Pressure Level) when 1mW power is applied. Sometimes the specs are given at 1Volt so 102dB/V means it puts out 102dB at 1V

*In general it ranges from 90dB/mW to 105dB/mW.*

**Impedance:**
usually given in Ohms (Ω) lower Ohmic headphones (between 16Ω and 64Ω) are intended for portable use (that is IF the sensitivity is high enough). Higher Ohmic versions (above 64Ω to 600Ω) are intended for home audio and studio use and should be driven from an amplifier that is capable of putting out enough voltage.

Basically: the lower the impedance the lower the needed voltage is needed to reach loud levels. For higher impedance headphones a higher voltage is needed. Voltage and impedance have a relation to power.

*In general it ranges from 16Ω to 600Ω. Some rare drivers go as low as 4Ω or as high as 2,000Ω, but these values are quite unusual.*

**In short:**
Low impedance headphones are intended for usage with portable gear.
Higher Ohmic headphones are not/less suited for portable gear unless an amplifier is used that can provide enough VOLTAGE but high impedance headphones are primarily intended for home and studio usage.

The lower the impedance and/or the higher the efficiency the louder it can play undistorted when used with portable gear such as MP3 players/DAPs. High impedance and/or low efficiency headphones will not go loud straight out of portable gear such as MP3 players/DAPs without distortion setting in.

The next part will go in depth to the most important factors mentioned above.

**Power** has a direct relation to **impedance**, voltage and current.

**Sensitivity** or efficiency has a direct relation to applied power and SPL (Sound Pressure Level).
Power, Voltage, Current and Resistance.

Power (P in Watts) = Voltage (U in Volts) x Current (I in Amps).... P=UxI

Since the power levels in headphones are rather small it is better expressed in mW (0.001W) and mA (0.001A)

Voltage levels are in the Volts range, Impedance is in the Ohms (Ω) range so these are not expressed in milli-something.

In the specifications that come with headphones voltage and currents are (almost?) never mentioned. Only nominal impedance and maximum rated power are usually supplied. Yet, voltage and current is what is being delivered by music players and amplifiers. In some cases amplifiers state maximum output power and the range of headphones (they feel) could be driven properly by it. Sometimes output powers at various impedances are mentioned. Notice how these power ratings vary.

Some math comes in handy at this point as voltages and currents can be derived from impedance and power numbers. Ohms law is paramount here. It states U=(voltage in Volts) = I (current in Amps) X R (resistance in Ω)... U=IxE. Impedance is not the same as resistance but around 1 kHz they are usually around the same value. The measured DC resistance is thus about the same as the given impedance at 1 kHz in Ohm (Ω). At low and the highest frequencies the impedance is usually higher (depends on the type of drivers used) but is not of importance for these calculations.

So... U=IxE and P=UxI In these two formulas all four quantities are present; P, U, I and R and since there is a linear relation between these quantities you can juggle with them.

I=U/R and P=UxI so one can substitute I, U and R in the equation P=UxI.
P=UxR and also P=Ix(IxR) normally noted as P=U^2/R or P=I^2R. When two of the values are known the 3rd one can be calculated. In the case of headphones the P (mW) and R (impedance in Ω) is known and thus the accompanying current and voltage can be calculated. U=PxR and to get the U you simply have to take the square root (√), so U=√(PxR). To calculate the current the formula I=√(P/R) is used, again the I can be calculated by taking the square root. I=√(P/R)

Note the values are in Amps, Volts, Ohms and Watts but headphone powers are usually given in milliwatts (mW) so have to be divided by 1,000 to get the Amps, voltages and resistances right.

The real life maximum voltages and currents that are needed are given in the tables and graphs below.

The table and graph below will give the voltages that are needed to give the powers in the 4 columns (1mW, 10mW, 200mW and 1W) for the given impedances.

As can be seen in the table and graph the low impedance headphones do not need much voltage to reach higher power levels. A common 32Ω headphone for instance only needs 2.53 Volts to reach it's maximum power, yet a 300Ω (also a common value) needs 3x that voltage (7.75V).

A 600Ω headphone needs 11V to reach 200mW. Should one supply the same voltage to a 16Ω headphone it would be receiving 7.6 Watt and would literally go up in flames. That is... if a certain current limiting function were not available. In practice it is, usually in the form of an added output resistance or a current limiter.

In short: For low Ohmic headphones (8Ω to 16Ω) 3V is about the maximum to drive them to full power. Higher Ohmic headphones (120Ω to 600Ω) need a considerable higher voltage to reach their maximum rating. It should stay below 12V.

The needed currents (in mA) is given in the table and graph below. When the figures are compared to those of the voltages above it is clear the lower Impedance headphones require more current (but less voltage) to reach the specified power levels. High Ohmic headphones require less current yet need a higher voltage to reach the specified powers.

It is evident it is not easy to build an amplifier that can PROPERLY drive all kinds of headphones. This is the challenge the engineers/designers face. It is also why some amplifiers cannot drive certain headphones well and others can. A Matter of selecting the right amplifier for the right headphone.

This is not an easy task if all you have is little relevant info from the manufacturers of players and amplifiers.
Efficiency

Most headphones have a power rating of 200mW (0.2W) so very little power is needed which is handy because battery fed devices can last long. This doesn't mean a headphone has a continuous power on it nor that it needs it. The amount of power (together with the sensitivity) determines how loud it plays.

Given the fact average headphones have an efficiency of around 95dB/mW the SPL at 200mW is 118dB, which already is close to the pain threshold so more power is generally not needed. The range in efficiency is between 85dB/mW and 105dB/mW. This doesn't seem to be a wide spread but 10dB is a doubling in perceived 'loudness'. 20 dB is a 4 fold higher perceived SPL. So the 105dB/mW will play 4 times as loud as the 85dB/mW headphone when the applied power is the same. This is the biggest reason why headphones are said to be 'difficult to drive'. They simply need a higher voltage and thus the volume knob needs to be turned up. If the amplifier that drives the insensitive headphone runs out of voltage it simply won't play loud. Another 'hard to drive' myth comes from headphones being driven from low output resistance amplifiers while some headphones NEED to be driven from higher Ohmic amplifiers, simply to sound the way they were designed to. My article about impedance and resistance goes more in depth about this aspect. The specified power rating is for 'continuous' power but in practice the average power levels are lower so when a headphone receives short peaks that exceed 200mW they should be able to cope with that. A 3dB headroom is still safe meaning 400mW peaks won't destroy the headphone. An average headphone with a sensitivity of 100dB/mW can thus produce peaks of 126dB SPL without being damaged. Therefore a little headroom (an amplifier that can supply more than the 'expected' maximum output voltage can have benefits.

How many dB's SPL do we need?

The table on the right will give you an idea how loud things sound. With these numbers in mind you can calculate how much power would be needed to obtain the levels we like to reach. It is safe to say we really do not want to cross certain levels so exceeding 120 dB is not very desirable for longer periods.

For a really insensitive headphone, that has an efficiency of 85dB/mW, to reach 120dB SPL it would need 40dB more power. A factor 10,000 represents 40dB (in power, not in voltage) so 10,000 mW = 10W

Such an headphone needs to have a 10W rating at least. Since such headphones usually only have a 1W rating it is safe to say it will never play extremely loud, yet can reach 110dB which is very loud, yet not deafening.

Average headphones have an efficiency of around 95dB/mW and only need 25dB more power which is a comfortable 300 times. So only 300mW is needed to drive such an headphone to the pain threshold. To play such an headphone very loud (110dB) only 30mW is needed.

So average sensitive headphones will already play quite loud on low output powers. Very sensitive headphones (105dB/mW) only need 30mW to reach the pain threshold and thus will play very loud on portable players such as MP3 players, but only IF this headphone also has a low impedance.

Some brands specify efficiency in dB/V and not in dB/mW. In order to get the dB/mW figures the power that represents 1V needs to be calculated. This means the impedance must be known.

\[ P = \frac{U^2}{R} \]

\[ P = \frac{1^2}{R} \]

A 32Ω headphone at with 1 Volt on it dissipates 31mW. A 300Ω headphone with 1V on it dissipates 3.3mW.

To calculate how much dB difference this is when 1mW would be applied the following equation is used 10 x LOG(impedance) and the outcome in dB is to be subtracted from the given dB/V or may be given SPL/V

\[ \text{A 32Ω headphone is specified as having 108dB/V this means it will give an SPL of 108dB when 31mW is fed into it. 10 x LOG(31) = 14.9dB so when this is subtracted from 108dB you end up with 93dB/mW.} \]

A 300 Ohm headphone with 102dB/V dissipates 1/300 = 3.3mW. 10 x LOG(3,3) = 5.3dB subtract that from 102dB and you get an efficiency of 96,8dB/mW.

<table>
<thead>
<tr>
<th>Source</th>
<th>SPL(dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold of Hearing</td>
<td></td>
</tr>
<tr>
<td>Quietest audible sound for persons with excellent hearing under laboratory conditions</td>
<td>0</td>
</tr>
<tr>
<td>Quietest audible sound for persons under normal conditions</td>
<td></td>
</tr>
<tr>
<td>Virtual silence</td>
<td>10</td>
</tr>
<tr>
<td>Rustling leaves, quiet room</td>
<td>20</td>
</tr>
<tr>
<td>Noticeably Quiet - Voice, soft whisper</td>
<td></td>
</tr>
<tr>
<td>Quiet whisper (1m)</td>
<td>30</td>
</tr>
<tr>
<td>Home</td>
<td>40</td>
</tr>
<tr>
<td>Moderate</td>
<td></td>
</tr>
<tr>
<td>Quiet street</td>
<td>50</td>
</tr>
<tr>
<td>Loud - unusual background, conversation @ 1m</td>
<td>60</td>
</tr>
<tr>
<td>Conversation</td>
<td></td>
</tr>
<tr>
<td>Loud - Voice conversation 0.3 m</td>
<td></td>
</tr>
<tr>
<td>Inside a car</td>
<td>70</td>
</tr>
<tr>
<td>Car (15m)</td>
<td></td>
</tr>
<tr>
<td>Vacuum cleaner (3m)</td>
<td></td>
</tr>
<tr>
<td>Freight Train (30m)</td>
<td></td>
</tr>
<tr>
<td>Loud singing</td>
<td>75</td>
</tr>
<tr>
<td>Loud – too loud when using the phone</td>
<td></td>
</tr>
<tr>
<td>Automobile (10m), Pneumatic tools (15m)</td>
<td>80</td>
</tr>
<tr>
<td>Buses, trucks, motorcycles (15m)</td>
<td></td>
</tr>
<tr>
<td>Motorcycle (10m)</td>
<td>88</td>
</tr>
<tr>
<td>Food blender (1m), Jackhammer (15m), Bulldozer (15m)</td>
<td>90</td>
</tr>
<tr>
<td>Subway (inside)</td>
<td>94</td>
</tr>
<tr>
<td>Very Loud</td>
<td></td>
</tr>
<tr>
<td>Diesel truck (10m)</td>
<td>100</td>
</tr>
<tr>
<td>Lawn mower (1m)</td>
<td>107</td>
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<tr>
<td>Pneumatic riveter (1m)</td>
<td>115</td>
</tr>
<tr>
<td>Threshold of Discomfort</td>
<td></td>
</tr>
<tr>
<td>Large aircraft (150 m over head)</td>
<td>110</td>
</tr>
<tr>
<td>Chainsaw (1m)</td>
<td>117</td>
</tr>
<tr>
<td>Deafening, Human pain limit</td>
<td></td>
</tr>
<tr>
<td>Amplified Hard Rock (2m)</td>
<td>120</td>
</tr>
<tr>
<td>Siren (30m)</td>
<td></td>
</tr>
<tr>
<td>Jet plane (30m)</td>
<td>130</td>
</tr>
<tr>
<td>Artillery Fire (3m)</td>
<td></td>
</tr>
<tr>
<td>Short exposure can cause hearing loss</td>
<td></td>
</tr>
<tr>
<td>Military Jet Take-off (30 meter)</td>
<td>150</td>
</tr>
</tbody>
</table>
Amplifier capabilities

What are the specifications we need to look for in amplifiers?
The better brands specify how much power can be delivered in a specific impedance.
In this case it is simply a matter of looking if the given output powers are high enough to obtain the desired maximum output levels.
If only a single (and optimistic) output power is given and the only other statement is ‘suited for headphone between 32Ω and 300Ω’ it is unknown how much power is available for certain impedances.

When we look at the data above it is clear the maximum SPL that can be achieved is determined by the efficiency (dB/mW) and maximum power rating (mW).

How much VOLTAGE or CURRENT is needed to reach those power levels depends on the impedance.
High impedance headphones that need to reach their maximum rating (say 200mW) need more voltage but less current.
This will be in the range of 6V to 10V and currents drawn will be between 20mA and 40mA.
Low impedance headphones need less voltage to reach the 200mW level.
This will be in the 1.5 to 3V range but needs somewhat higher currents between 80mA to 150mA.
For headphones with higher power ratings (say 4 times higher, around 0.8W) the voltage needed and current drawn is 2 times higher.

If you want to drive high impedance headphones you need a higher voltage.
When you only need to drive low impedance headphones a small voltage is already enough.
A clue in this matter is the supply voltage of the amplifier in question but this might be misleading.
Amplifiers (PA2V2 for instance) or portable players that are fed from 2 AA or AAA batteries (or even with rechargeable’s with an even lower voltage) can put out only 1V or even less (500mV to 700mV).

When you look at the voltage table above it is clear 0.5V to 1V simply will not give a lot of power, certainly not if higher impedance headphones are to be used.
In case the device in question has an internal DC/DC converter that boosts the internal voltage to a much higher one (Superlux HA3D for instance) the maximum output voltage of such an amplifier can easily reach several volts, but the battery life will be much shorter because of the drawn power (DC/DC converter efficiency + higher output power of the amplifier).

In general the power supply voltage determines how much voltage an amplifier can deliver.
To get an output voltage of 5V you need a power supply voltage that is at least 3x higher, so 15V DC (or +/- 7.5V)
This is because the mentioned voltages are so called RMS (Root Mean Square) voltages, also called effective voltages.
These effective or RMS voltages deliver the same amount of heat (power) in a resistance as a DC voltage of the same value. So 5V DC and 5V_{RMS} = 5V_{eff} SINEWAVE deliver the same power.
Since the peak voltage of an RMS of a sine-wave is \sqrt{2} = 1.41 times higher the peak voltage is 5x1.41 = 7.05V
But a sine-wave has a positive and negative voltage swing so this doubles the calculated voltage yet again. 2x7.05 = 14.1V.
Add the slight loss of voltage swing in the output stage of an amplifier and 15V is about the minimum voltage that is needed to make a 5V_{RMS} sine-wave.

So what can we expect (in output voltage swing) from the following devices:

2.4V (3V with alkaline) dual AA(A) battery fed amplifier or MP3 player without DCDC converter:
0.8V_{RMS} (1V_{RMS} with alkaline) = 40mW into 16Ω, 20mW into 32Ω, 2mW into 300Ω

4 AA battery fed amplifier without DCDC converter:
1.3V_{RMS} (with alkaline) = 100mW into 16Ω, 50mW into 32Ω, 6mW into 300Ω

single 9V battery fed (C'moy). There is a little snag with this one as op-amps are not really intended to drive low impedances and the current limiter kicks in. The behavior of the inbuilt current limiter can be bad but also behave reasonably well. Most op-amps have a current limit of around 40mA (some lower some a bit higher) only more specialized op-amps can deliver higher currents of 100mA to even 250mA. Also here one needs to keep in mind that the drawn AC current is an RMS value and thus \sqrt{2} = 1.41 times smaller so a current limited at 50mA will only give 35mA_{RMS} current:
2.9V (50mA op-amp used) = 20mW into 16Ω, 40mW into 32Ω, 78mW into 64Ω, 70mW into 120Ω, 28mW into 300Ω.

Single 12V_{DC} fed amplifier with buffered output:
3.9V (250mA op-amp used) = 0.5W into 16Ω, 0.47mW into 32Ω, 230mW into 64Ω, 120mW into 120Ω, 50mW into 300Ω.

Dual 9V battery fed C'moy type with op-amp output:
6V (50mA op-amp used) = 20mW into 16Ω, 40mW into 32Ω, 78mW into 64Ω, 150mW into 120Ω, 120mW into 300Ω.

Dual 9V battery fed with buffered output (transistor, MOSFET or 250mA opamp buffer):
6V (250mA op-amp used) = 500mW into 16Ω, 1W into 32Ω, 550mW into 64Ω, 300mW into 120Ω, 120mW into 300Ω.
As can be seen in the numbers from the higher voltage amplifiers with buffered output (not the C'moy op-amp output types) the output power for 16 Ω to 64 Ω already exceed the 200mW limit for these headphones, so one should be careful with those amplifiers and low impedance headphones.

It is also evident that none of these amplifiers are able to drive 300Ω and 600Ω headphones to their maximum power. It should be noted that they already come very close to that so very loud levels are possible. To drive the higher Ohmic headphones to their maximum levels higher voltage rails are needed. Amplifiers with +/-12V, +/-15V or even +/-20V can drive these headphones with ease.

It is important, however, that the amplifiers that can deliver these voltages have a form of current limiting. In case this is not present (Panda or SC Class-A without added output resistors) and a low impedance headphone is connected high currents can be the result. High enough to burn 200mW voice-coils to a crisp when accidentally run at full power. An example (let’s say the current is limited to 1A due to power supply limits) output voltage 8V_RMS:

\[
\begin{align*}
4W & \text{ into } 16Ω, 2W & \text{ into } 32Ω, 1W & \text{ into } 64Ω, 500mW & \text{ into } 120Ω, 200mW & \text{ into } 300Ω, 100mW & \text{ into } 600Ω.
\end{align*}
\]

Only headphones with an impedance above 120Ω will be safe to use. For this reason a form of current limiting must be used. This can be done by an active current limiter in the output stage (this will keep the output resistance low) or by limiting the current with a resistor in series with the headphones. This resistor is internal in the amplifier and represents the output resistance of this amplifier.

Because this problem (the too high power at lower impedance headphones) is known to headphone manufacturers they use standardized (120Ω) resistors when designing headphones and ‘tune’ the sound so it sounds as intended when this output resistance is used. Smaller output swings of amplifiers warrant smaller output resistors. The effects of this are discussed in my impedance article.

Values without output resistor or current limiter:

\[
\begin{align*}
(8V_{\text{RMS}}) & = 4W \text{ into } 16Ω, 2W \text{ into } 32Ω, 1W \text{ into } 64Ω, 500mW \text{ into } 120Ω, 200mW \text{ into } 300Ω, 100mW \text{ into } 600Ω.
\end{align*}
\]

Values WITH output resistor (68 Ohms):

\[
\begin{align*}
(8V_{\text{RMS}}) & = 145mW \text{ into } 16Ω, 200mW \text{ into } 32Ω, 230mW \text{ into } 64Ω, 217mW \text{ into } 120Ω, 140mW \text{ into } 300Ω, 90mW \text{ into } 600Ω.
\end{align*}
\]

As can be seen the added output resistance makes sure all headphones receive the right amount of power. The same can be reached if the amplifier has a current limiter set to 180mA but in this case the output resistance of the amplifier will not be 68Ω but can be close to 0Ω. Whether this low Ohmic output resistance will sound better than the higher Ohmic one is open for debate. A lot of high impedance headphones might sound better with the higher output resistance of an amplifier, low impedance headphones might sound better from a current limited amplifier. Ah... choices... and lets not forget most amplifier designs do not specify output resistance or the value of their current limiters when used.

How much power does an amplifier draw that can successfully drive a wide range of headphones. This amplifier has high voltage rails (even higher because of internal voltage regulators that need a minimal voltage drop to work) and can provide enough current to drive low impedance headphones as well. The voltage is +/-20V for instance (so 40V in total) and the current limiter is set for 250mA. This is for 1 channel only of course so the current needs to be doubled, so 0.5A peak.

\[40V \times 0.5A = 20Watt \ldots\] all this power just to provide any connected headphone to a maximum of 0.2W.

I hope this article has shed some light on this dark matter.

Frans de Gruijter